

BORE POLISHING IN A RUNNING DIESEL ENGINE

by

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ABSTRACT

A review of the literature on the subject of bore polishing in diesel engines reveals two important limitations. Firstly, the mechanisms of bore polishing have not been properly defined and secondly there is no evidence of a reliable bench test device to simulate bore polishing.

The aims of this study were: a) To determine whether an effect resembling bore polishing could be produced in a simple bench test device, b) to compare test results with full scale tests and practice, c) to extend our knowledge of possible bore polishing mechanisms and d) to investigate the effect of a commercial antiwear additive on bore polishing occurrence. ;

The metallurgy used in these tests was chrome plated piston ring on cast iron cylinder liner from a commercial engine. The results have shown that an effect resembling bore polishing in full scale tests and practice is achieved, and a test device is capable of distinguishing between polishing and non-polishing oils. Several analytical techniques have been used and further knowledge on bore polishing has been obtained. In particular it is suggested that three wear mechanisms are specifically implemented in bore polishing: abrasive, delamination and corrosive wear. The role of antiwear concentration has been highlighted and an optimum concentration observed for low polishing severity. An attempt has also been made to define the nature of a bore polished surface.

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NOMENCLATURE

|          |   |
|----------|---|
| A.P.I.   | American Petroleum Institute                |
| A.S.T.M. | American Society for Testing Materials      |
| B2       | Base Stock                                  |
| C        | Commercial additive, additive concentration |
| C1-C6    | Commercial oils                             |
| C.E.C.   | Coordinating European Council               |
| C.E.V.   | Carbon Equivalent Value                     |
| C.L.A.   | Centre Line Average                         |
| D.B.D.S. | Dibenzyl Disulphide                         |
| E        | Reactivity Constant                         |
| E.P.     | Extreme Pressure                            |
| H.F.R.   | High Frequency Reciprocating                |
| I/P      | Input                                       |
| M.I.R.A. | Motor Industry Research Association         |
| M.P.A.   | Microprobe Analysis                         |
| O/P      | Output                                      |
| R        | Gas constant                                |
| S.E.M.   | Scanning Electron Microscope                |
| T        | Absolute temperature                        |
| T.D.C.   | Top Dead Centre                             |
| V.I.     | Viscosity Index                             |
| ZDDP     | Zinc Dialkyldithiophosphate                 |
| $\mu$    | Friction Coefficient                        |

C H A P T E R 1

Literature Survey and Introduction to Project

## 1.1 Introduction

### 1.1.1 Background

Since early times lubrication in one form or another has been essential in any environment in which two surfaces rub together.

A lubricant has four basic roles:

- 1) The reduction of friction and wear.
- 2) The removal of heat from rubbing surfaces.
- 3) The removal of debris (metallic or otherwise) from the surface.
- 4) The protection of the surface from corrosion.

This study concerns the first of these roles - the reduction of friction and wear of two opposing surfaces. When acting in this role the lubricant provides a low shear material between asperities of the two rubbing surfaces. It is common to recognise three types of low shear lubricant film.

- 1) Boundary film
- 2) Elastohydrodynamic film
- 3) Hydrodynamic film.

In boundary lubrication, surface interaction is of great significance. Friction between surfaces is largely influenced by surface characteristics, e.g. surface finish, hardness and metallurgy of opposing materials and the chemistry of the lubricant. The two surfaces are in contact for a large proportion of the time. Film thicknesses

are typically less than  $0.1\mu\text{m}$  and consequently solid/solid interaction is very important. Elastohydrodynamic oil films are of the order of  $1\mu\text{m}$  thickness, again comparable with surface roughness. Some solid/solid contact generally occurs and this regime often involves a considerable boundary component. With hydrodynamic oil films the thickness is of the order of  $10\mu\text{m}$ , and the two surfaces are effectively separated.

### 1.1.2 Boundary Lubrication

Boundary lubrication is the regime relevant to the study described in this thesis and a fuller description now follows.

Boundary lubrication involves the formation of a low shear strength film between rubbing surfaces. Such films are thought to form on clean metal or metal oxide surfaces by the adsorption of water and polar organic substances from both air and from lubricants. Because the effect is a surface phenomenon it greatly influences boundary lubrication. This has meant that additives can be usefully added to lubricants to improve their friction and wear performance by forming boundary films. There are three types of additives commonly recognised.

#### 1) Oiliness additives

Very pure mineral oils are themselves poor lubricants since they have only a weak tendency to adsorb on rubbing surfaces to provide a low shear strength film. The

addition of small quantities of fatty acids and esters causes an adsorbed layer to be formed since the oiliness additives possess a hydroxyl (OH) or carboxyl (COOH) radical on one end of the molecular chain. These molecules are polar and readily adhere to the surface. The adsorbed layer is temperature dependent in that surface coverage is not static but is formed by a dynamic equilibrium of molecules adsorbing and desorbing. This equilibrium is inversely related to temperature and at temperatures above 150°C there is insufficient coverage to maintain adequate lubrication (1). Oxidation of the base oil also forms surfactants which form polar bonds with the surface.

## 2) Antiwear additives

Antiwear additives generally contain phosphorus atoms. They have the property of chemically reacting with rubbed metal surfaces at relatively low temperatures (70-150°C) to form a low shear strength film. The key feature of this film is that it protects the surface from extensive wear - unlike extreme pressure additives (see next section). The exact mode of action is not yet clear. Some authors consider the shear film found to be a very thin organophosphate layer (<10nm) whilst others consider that thick viscous layers are formed. A particularly common antiwear additive and one involved in this study is zinc dialkyldithiophosphate (ZDDP). This is discussed in more detail on page 20

### 3) Extreme Pressure (E.P.) additives

These consist of organic compounds containing a reactive element (e.g. sulphur, chlorine or phosphorus). Sulphur alone is highly corrosive although can act to form antiwear films. Sulphur is not used alone but is combined chemically to form organic compounds which provide low shear strength films. An example of an E.P. additive is dibenzyl disulphide (DBDS). E.P. additives are thought to form thick inorganic salts (sulphide or chloride) under high temperature rubbing conditions. E.P. films are not generally considered to limit wear, however. They may indeed cause rapid corrosive wear under overload conditions.

An added complication is that other additives, such as detergents and dispersants, in engine oils can reduce the effectiveness of the above boundary layer additives.

This thesis is concerned with crankcase lubricants. These generally contain one antiwear additive, zinc dialkyl-dithiophosphate. This has the general form shown below.

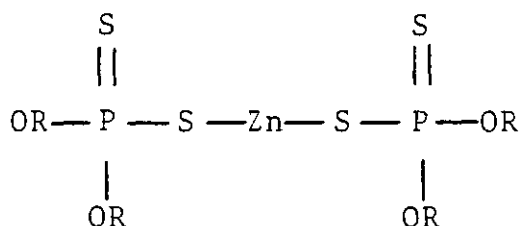


FIG 1.1 GENERAL FORM OF A ZDDP

Although generally speaking an antiwear additive, it can also be quite corrosive, and behave as an E.P. additive. It also doubles, in crankcase lubricants, as an antioxidant.



The mechanism of its action is not fully understood and there follows a brief description of the generally accepted method of action.

The ZDDP is not substantially chemisorbed on iron but its decomposition products are adsorbed and these supply the antiwear function ( 2 ). The decomposition products form two distinct types of lubricant film.

- 1) Zinc polyphosphate film associated with the antiwear properties of a ZDDP.
- 2) Mixed alkyl sulphides (from decomposition) and iron oxide ( $\text{Fe}_2\text{O}_3$ ) provide iron sulphide ( $\text{FeS}$ ) in the form of ternary eutectic with iron oxide ( 3 ). The iron sulphide film is more associated with high temperatures (above  $150^\circ\text{C}$ ) and consequently extreme pressure action. Watkins ( 3 ) also highlights the role of sulphur and notes its presence in severely stressed metal contacts. This appearance of sulphur will be discussed in more detail in Chapters 4 and 5.

The presence of an iron sulphide film at high temperature could suggest that base oils with some sulphur present in them have a weak E.P. action at high temperatures.

ZDDP additives have several drawbacks. In particular they can enhance corrosion of some metals and are also thought to increase the occurrence of plastic deformation ( 4 ) although the process is not yet understood.

Recently, under the stimulus of energy conservation, oil companies have begun to add oiliness additives to their high performance gasoline engine lubricants as a friction reducer. The exact structure of these are commercially confidential. They are surfactants often with a phosphorus content. They are not relevant to this thesis which is concerned with diesel engine lubricants.

### 1.1.3 Wear

The Institution of Mechanical Engineers defines wear as "progressive loss of substance from the surface of a body brought about by mechanical action (usually it reduces the serviceability of a body, but it can be beneficial in its initial stages of running-in)".

This section describes several types of wear relevant to this thesis.

#### 1) Adhesive Wear

This occurs when two metals weld together when their nascent surfaces are exposed. The two surfaces are inadequately protected by lubricant films and the oxide layer is abraded allowing the two surfaces to adhere to one another. Material is transferred from one surface to another, leaving a wear scar. If the process is continued, scuffing can occur. This is described on page 24. Adhesive wear may be limited by increasing the reactivity of the lubricant, and thus forming more powerful boundary lubricant layers.

## 2) Corrosive Wear

The removal of reacted surface layers formed by E.P. additives, oxygen and other corrosive agents is termed corrosive wear. The rate of formation of reacted films often follows Arrhenius' law:

$$\text{Reaction rate} = K.C.e^{-E/RT}$$

where C is the concentration of reactive component in the oil (e.g. E.P. additive)

E is a constant related to the reactivity of the E.P. additive

T is the absolute surface temperature.

The rate of corrosive wear is greatly affected by this reaction rate and hence additive concentration. There is clearly an optimum balance between corrosive and adhesive wear for additive concentration. Rowe (5) demonstrated that an optimum concentration of ZDDP could produce a satisfactory balance of corrosive and adhesive wear rates.

Corrosion in diesel engines often occurs by the formation of dilute sulphuric acid from sulphur and water obtained in the combustion process. The sulphuric acid selectively attacks the ferrite in the cast iron matrix.

This can cause pitting and weakening of the surface structure. Selective attack is particularly pertinent to the middle of the liner and there is a need for increased corrosion resistance in this area (6).

### 3) Abrasive Wear

Abrasive wear is caused by hard particles penetrating the surface, thereby producing characteristic grooving in the sliding direction.

Two body abrasive wear is the transfer of particles across a surface, whilst three body abrasive wear leads to high stresses when foreign particles are introduced between two opposing surfaces.

Abrasive wear may be alleviated by increasing the hardness of opposing surfaces, increasing oil film thickness and reducing surface roughness.

### 4) Delamination Wear

The delamination theory of wear postulated by Suh (7) consists of several steps.

1. Plastic shear deformation accumulates on the surface of the softer material.
2. Repeated pass leads to the nucleation of subsurface cracks around existing voids.
3. Extension of the cracks, due to further deformation, are propagated parallel to the surface.
4. When the cracks finally shear to the surface long thin wear sheets delaminate. The thickness of the

particles is dependent upon material properties and the coefficient of friction.

The transmission of forces to the surface involves adhesion and abrasive wear, which are influenced by choice of lubricant additive, surface hardness and finish and a number of other factors. The formation of the wear particle is thought to be strongly dependent upon material defects ( 8). As yet the analysis has not been used to formulate an equation to predict wear.

A number of papers have been published on the topic of delamination wear, to which the reader is referred ( 9).

#### 5) Fretting Wear

Fretting occurs between surfaces which oscillate at low amplitude. Work carried out by Ohmae and Tsukizoe (10) indicates that slip amplitudes of 70µm and above are not prone to the phenomenon. Fretting is a special category of corrosive wear and results from oxidised oil intermediates themselves oxidising the rubbed metal. Oils with a anti-oxidant (such as ZDDP) may be used to limit the production of oxide debris which may rapidly abrade surfaces by three body abrasion (11).

#### 1.1.4 Scuffing

The Institute of Mechanical Engineers defines scuffing as "gross damage characterised by the formation of local welds between sliding surfaces".

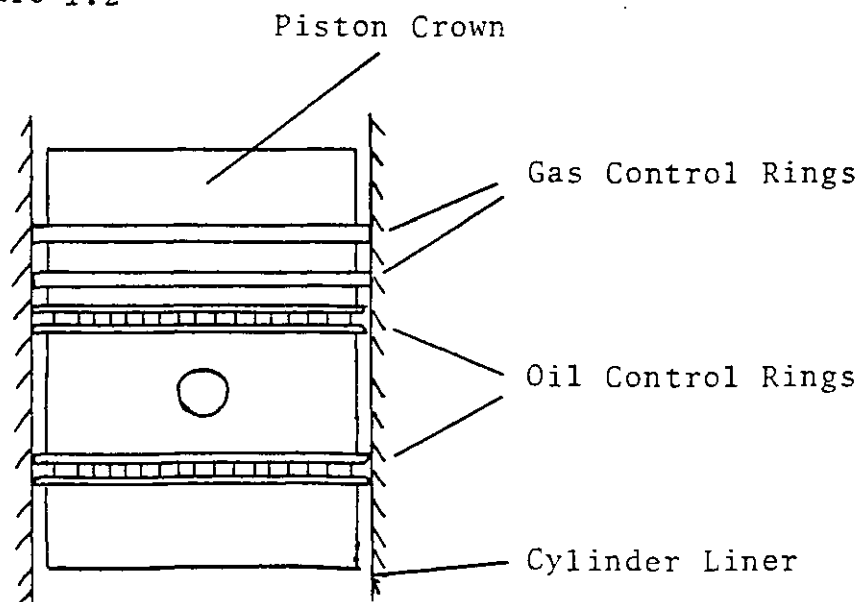
The general mechanism is that scuffing is initiated by the generation of very high micro-area temperatures at the surface interface. Welding occurs between the opposing surfaces, resulting in cutting wear by weld fragments. The temperature rise is a function of the oil film and its boundary lubrication properties as well as the materials employed and the surface finish of the working parts (12).

## 1.2 CYLINDER LINER LUBRICATION

### 1.2.1 Introduction

The study in this thesis is concerned with diesel engines and this section deals briefly with the wealth of information associated with them.

In a diesel engine a piston compresses air and at the top of the stroke (top dead centre - T.D.C.) fuel is injected and ignites forcing the piston down the cylinder. The exhaust gases are sealed by a series of piston rings as shown in Figure 1.2



There are a range of piston rings used in diesel engines. The upper rings deal primarily with gas control with some oil control function, whilst the lower rings have a primary oil control function. In this context it is common to have several types of ring: compression, single taper, oil control, double taper (barrel), oil scraper and so on. The primary functions of the rings are:

1. To control leakage of combustion gases past the piston.
2. To keep crankcase oil from leaking past the piston and being lost by combustion.
3. To transmit heat from the piston to the relatively cooler liner.

Clearly for the rings to be effective they must rub directly against the cylinder liner, so lubrication is essential.

#### 1.2.2 Operating Conditions

Throughout the cycle of a diesel engine there exists a wide range of operating conditions. The most severe conditions occur on the power stroke. Hamilton and Moore (13) found, using a Petter AV1 single cylinder diesel at maximum power output, the T.D.C. liner temperature was 246°C. McGeehan (14) also reports that piston crown land temperatures may be as high as 300°C. The cylinder pressures on the firing stroke have peak values of around 20MPa, although

the ring/liner pressure is about 10-15MPa. These conditions have a significant effect upon the oil film thickness, particularly at T.D.C. where the piston changes direction. Hamilton and Moore (15,16) have indicated with tests on the Petter AV1 and Petter AVB diesel engines that minimum oil film thicknesses are of the order of 0.2 to 0.4 $\mu$ m, i.e. boundary lubrication with a small hydrodynamic component. Clearly under these conditions the environment at T.D.C. on the firing stroke is very severe.

### 1.2.3 Running-in

The first stage of liner wear is termed 'running-in' when the engine parts are conforming to each other's profile. Running-in is said to be complete when the engine will accept full load with a permissible value of oil consumption (17). Montgomery (18) reports that running-in is not necessarily characterised by metal distortion but reports a glaze is formed which is composed of graphite from the cast iron cylinder liners. Fursund (19) also reports observing this glaze on diesel cylinder liners.

The Paramins report (20) defines the glaze as chemically formed from iron oxide, graphite and decomposition products from the fuel and lubricant. Running-in may be accelerated by the use of fuel additives which produce an abrasive ash on combustion (21). Running-in time was reported to have been reduced to a factor of 1/10 to 1/12th and this may be of economical advantage.

Neale (22) conducted a survey of the occurrence of scuffing and found that the majority of cases happened in the



early stages of engine life. Experience has shown that changes of lubricant, material and bore finish can significantly influence the incidence of scuffing during running-in.

#### 1.2.4 Service Problems

During the life of a diesel engine there will be different stages of serviceability. As mentioned in section 1.2.3, running-in of an engine may be time consuming and can also lead to scuffing. Further operation nearly always leads to conformity of the mating parts although catastrophic wear may result, leading to engine failure at early engine life. Scuffing in early engine life mainly consists of asperity interaction and micro-welding, and is normally self-correcting whereas scuffing in later engine life leads to accelerated wear and finally seizure.

Neale (22) reports that out of 83 engines surveyed only three reported scuffing in the late stages of running-in. In the majority of cases piston ring scuffing occurred before the engine was fully run-in. Eyre and Dutta (23) using a pin and disc machine investigated some of the metallurgical aspects of scuffing. They showed that scuffing takes place by plastic deformation of the surfaces which eventually fracture normal to the sliding direction. In the case of ferrous metals a white layer was formed, and appeared to be a result of scuffing rather than the cause. Under oxidising conditions the scuff condition was terminated when the surface became stable enough for an oxide film to

form. Prolonged rubbing oxidised the surface at the expense of the white layer. Similar layers have been reported by Rogers (24), who examined the surfaces of scuffed rings and liners and found these to be covered by a thin non-etching hard layer which appeared to be a form of iron carbide. The white layer seemed to be indicative of plastic deformation.

Neale (22) highlights two methods by which scuffing may be tackled. Firstly the rings and their environment can be designed to reduce scuffing and secondly the materials and surface finishes can be optimised to give greater scuff resistance. Full description of these techniques may be found in Neale's paper.

Another service problem, often encountered in turbo-charged diesels (i.e. those not naturally aspirated) is bore polishing of the liners. This is dealt with in much more detail in Section 1.3. A consequence of bore polishing is blow-by, in which the combustion gases leak past the ring pack causing a loss in compression and consequently engine efficiency.

Oil consumption may be a significant problem in diesel engines, although Neale (22) reports that scuffing problems are more widely documented when manufacturers attempt to reduce oil consumption. An increase in oil consumption implies that oil is burnt in the region of T.D.C., leaving piston deposits. These deposits have a significant role in the phenomenon of bore polishing.

#### 1.2.5 Bench Testing

The fundamental requirements of a test apparatus which is to simulate boundary lubrication conditions found at T.D.C. are listed by Azhder (25) and MIRA (26). These are:

- Close simulation of friction conditions.
- Constant geometrical contact.
- Ease and control of loading.
- Several tests from the same ring and liner specimen.

These conditions are realised in the High Frequency Reciprocating (H.F.R.) apparatus described by Mills and Cameron (27) and in more detail by Mills (28). The apparatus was modified and described by Shimauchi (29). Knight and Weiser (30) gave a review of suitability of existing test methods for present and anticipated European needs (1976). They comment on the necessity to develop a standard test for bore polishing.

Willn (26) describes the development of a test apparatus to investigate the performance of anti scuff oil additives. Correlation with field testing was found to be good (31). There have been a large number of bench testing devices reported for the simulation of engine conditions, in many cases correlation with field testing has been good.

### 1.2.6 Engine Oil Composition

In addition to the additives described in section 1.1.2 there may be many others, e.g. detergents, dispersants, viscosity index improvers, pour point depressants, anti-oxidants, emulsifiers and so on. Of these the first three are the most commonly found in most diesel engine lubricants. These are now briefly described.

#### 1) Detergents and dispersants

Detergents are metal soaps of high molecular weight, usually calcium or barium, the organic components are typically sulphonates or phosphates. To impart oil solubility an alkyl radical is introduced, making the detergent polar. The aim of the detergent is to hold in suspension oxidation products which would otherwise form unwanted deposits in the engine. Dispersants operate at low temperatures and also hold oxidation products in suspension. They consist of a hydrocarbon base with added polar groups such as carboxyls.

#### 2) Viscosity Index improvers

The change of viscosity of an oil with temperature is described by the viscosity index. A high viscosity index (V.I.) indicates relatively little change in viscosity with temperature. V.I. improvers have the capability of reducing the viscosity variation. They are long chain molecules and typically include polyacrylates and polymethacrylate esters.

### 1.3 BORE POLISHING

#### 1.3.1 Definition and Characterisation

Bore polishing in cylinder liners of diesel engines is evidenced by clearly defined areas of bright mirror finish on the liner surface (14). It is caused by local mechanical wear and usually occurs after long periods of running-in at high speeds and loads (20). One example where this phenomenon is encountered is turbocharged diesels, which are designed for a high power output.

A method of categorising the level of bore polishing has been proposed (20). The three categories were defined as:-

##### Light polish

Mirror finish overlaid on the original honing pattern.

##### Medium polish

Mirror finish showing faint overlaid honing pattern.

##### Heavy Polish

Mirror finish showing no traces of the original honing pattern.

McGeehan (14) states that bore polishing is characterised by a bright smooth (mirror) finish of less than  $5\mu$  in, with total absence of cross hatch pattern.

The method of characterising bore polishing by light, medium or heavy polish suggested by Dinsmore (32) and the Paramins Report (20) has been adopted by the author for analysis of results. Wilson and Calow (33) have adopted a visual approach to bore polishing in favour of surface roughness and talysurf profile methods. This technique has also been employed by the author, although the talysurf has been used to compare some worn surfaces, Page 105      The photographs on page 34 show a sectioned cylinder liner with polishing and a piston with crown deposits.

### 1.3.2 Mechanism of Bore Polishing

A review of the limited amount of literature on the subject of bore polishing gives very little conclusive information about the mechanism of bore polishing.

The first stage of wear in a cylinder liner is termed 'running-in'. There are two proposed mechanisms

TDC

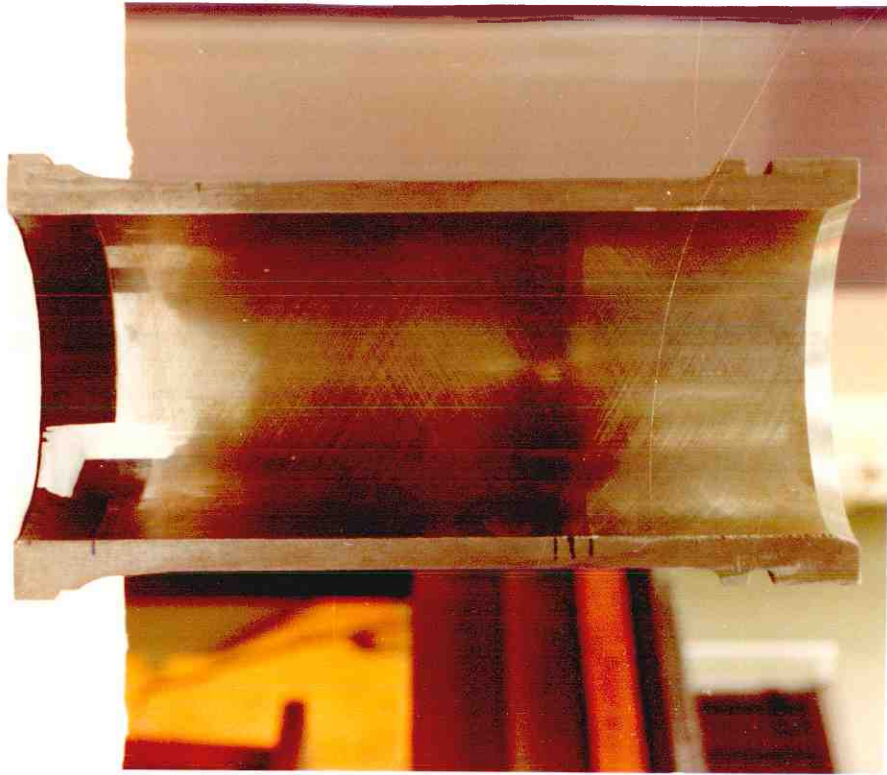


Figure 1.3 Cylinder with Bore Polishing (Petter AVB)

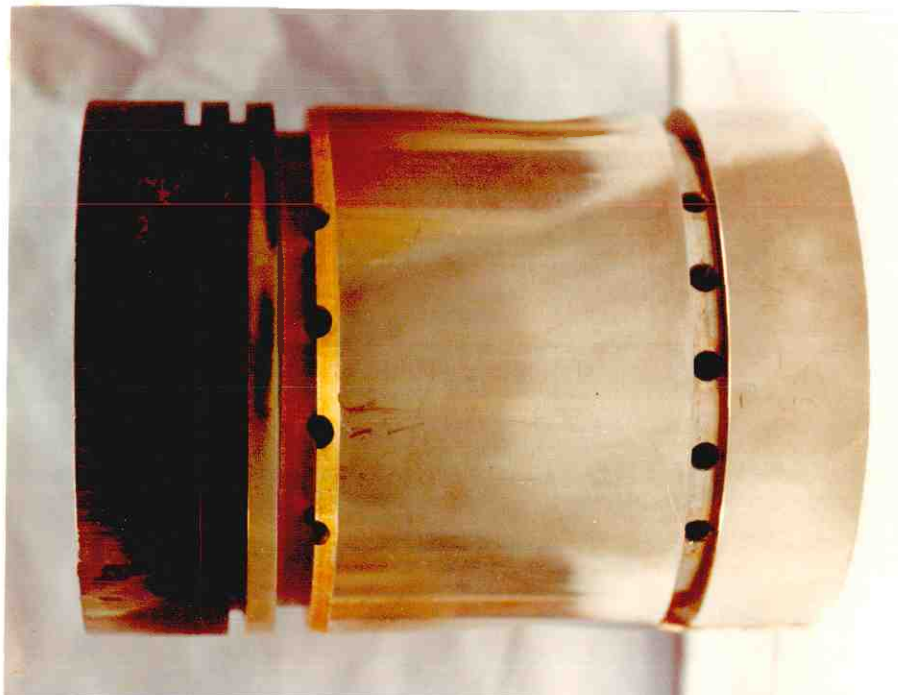


Figure 1.4 Piston from Petter AVB.

for this process. Østvik and Christensen (34) observed that running-in was due to squashing of asperities, whilst Montgomery (18) described the production of a glaze formed on the liner surface. Montgomery attributed the smoothing of the surface during running-in to the covering of asperities with glaze, which he states has iron oxide as an important constituent. The Paramins Report (20) defines the glaze as a skin, or coating, formed chemically on the liner surface from iron oxide, graphite and decomposition products from the fuel and lubricant. It can be 15-20  $\mu$  in thick. Fursund (19) also reports finding this glaze in cylinder liners. Sreenath and Ramon (35) conducted some running-in tests on a single cylinder diesel and concluded that running-in consisted of two phases. During primary running-in the asperities are flattened, whilst during secondary running-in the liner is smoothed by filling the valleys between asperities with wear debris or some self generated film. The wear particle atlas (36) describes a mixed shear layer of 1 $\mu$ m thickness which covers scratches and irregularities during running-in, also of iron oxide characterisation. There is clearly a wealth of evidence for the formation of a glaze formed during running-in, although there is no evidence to suggest that this could be a possible abrasive contaminant helping to promote bore polishing. Parsons (37) suggests two possible theories of bore polishing mechanisms.

- 1) Carbon deposits on the piston act as a lap (grinding paste) and polishes the liner.



2) Deposition on one side of the piston pushes it over causing it to bear heavily on the opposite side of the cylinder bore.

The Paramins Report (20) ascribes bore polishing to 1) and states that polishing has been found to extend above the area of ring travel. Häggh and Holmer (38) refer to a mechanism of bore polishing related to carbon deposits on the piston crown land. Wilson and Calow (33) on the other hand, report that polishing can occur below the bottom of ring travel with relatively clean piston skirts. They comment that bore polishing can occur early in engine life with almost deposit-free pistons. Parsons (37) further states that there is no conclusive proof for either of the two proposed mechanisms. He reports tests with two oils of 14% bore polish and 40% bore polish (measured by polished area ÷ swept area) in which the piston deposits were found to be identical. In conclusion, it may be said that whilst carbon deposits on the piston are a factor in the mechanism of bore polishing, there is insufficient evidence to show that this mechanism is of fundamental importance.

Parsons (37) reports on an investigation, carried out in the Lubrication Laboratory into the effect of oil insolubles in the H.F.R. bench testing device later described in Chapter 2.

Two oils were tested; one had been centrifuged to remove insolubles, whilst the other had insolubles

present in it. The H.F.R. device, which simulates piston ring and cylinder liner conditions at T.D.C., produced a polished wear surface for the uncentrifuged oil and a non-polished surface for the centrifuged oil. The conclusion drawn was that oil insolubles, whether carbonaceous or wear promoting contaminants, could enhance bore polishing. Ayel et al (39) suggests that the mechanism of bore polishing is by an abrasive 'grinding' paste, composed of hard carbon, in the oil. This acts between the ring and the liner. They also eliminated adhesive wear, scuffing wear, plastic deformation, corrosive wear and surface fatigue as a result of tests which they conducted. Abrasive wear has been observed by other investigators (40).

The Paramins Report (20) mentions that the piston ring could cause bore polishing, although it suggests that the normal ring face pressure would be unlikely to cause extensive polishing. Hamilton and Moore (41) measured the oil film thickness in a Petter AV1 diesel engine and found that a minimum value of 0.4  $\mu\text{m}$  was obtained and this was much less than the predicted values or the values found by previous investigators. In another paper, Moore and Hamilton (13) using a capacitance gauge just below T.D.C. found that in the supercharged Petter AVB diesel engine, a minimum oil film thickness of 0.2  $\mu\text{m}$  was observed. These values of oil film thickness indicate that the mechanism of piston ring and cylinder liner interaction cannot be ignored.

Kreuz (42) refers to the formation of sulphuric

acid, from sulphur trioxide and water, on the liner surface as a result of combustion products. He does not mention this as having an effect on bore polishing, however some diesels, e.g. Marine diesels, have high sulphur fuels and corrosive wear is often found as a consequence. The role of the fuel and its additives obviously plays a part in the mechanism of bore polishing.

In conclusion, the mechanism of bore polishing is complex. The most likely factors are :-

- 1) Hard Carbon deposits.
- 2) Oil insolubles (either carbonaceous or wear debris).
- 3) The run-in condition of the liner.
- 4) The fuel and its additives.
- 5) Piston ring interaction.

The literature does not give a clear indication which of these factors is the most important.

### 1.3.3 Effect of bore polishing

The onset of bore polishing is characterised by increasing oil consumption and blow-by (14,33). The Paramins Report (20) mentions that there appears to be a change in the mode of oil distribution at the polished surfaces, perhaps with a lessening of the ability of the surface to retain oil. Blow-by occurs, i.e. exhaust gases leak past the piston rings, and

eventually lubricant breakdown, which leads to scuffing of the liner surface and eventual seizure. The effect of blow-by in Diesel engines is to reduce the compression ratio i.e. the ratio of pressure at T.D.C. to that at bottom dead centre. Since the efficiency of the engine is closely linked to the compression ratio, blow-by causes the engine to be less efficient. For small bore polishing percentages (this will be discussed in more detail in Chapter 4) blow-by is not a serious problem, however for large bore polishing percentages blow-by is associated with loss of power and efficiency as well as high oil consumption. Furthermore large areas of bore polishing increase the likelihood of scuffing failure. Clearly bore polishing on a large scale is unacceptable whilst on a small scale it may be tolerated. This thesis attempts to define tolerable and unacceptable bore polishing percentages. This is discussed in Chapter 4.

#### 1.3.4 Reduction of bore polishing

Various methods have been employed to reduce cylinder liner wear and bore polishing. Furuhashi and Hiruma (43) report on a series of tests in which the crown land shape was altered. The crown land shape (a) on page 40 gave very high oil consumption whilst profile (b) gave very low oil consumption. The main observation from these tests was that oil on the cylinder wall in case (a) was scraped up by the piston land edge and burnt by the combustion flame. In case (b) the oil was not scraped up and was not burnt by the combustion flame. Consequently carbon deposits were found with (a) but not with (b). Dinsmore(32) also mentions cutting back the crown land and states that it minimises hard carbon build-up on the crown land. It is clear that the crown land profile is important. The effect of piston misalignment has been investigated by several experimenters, in particular

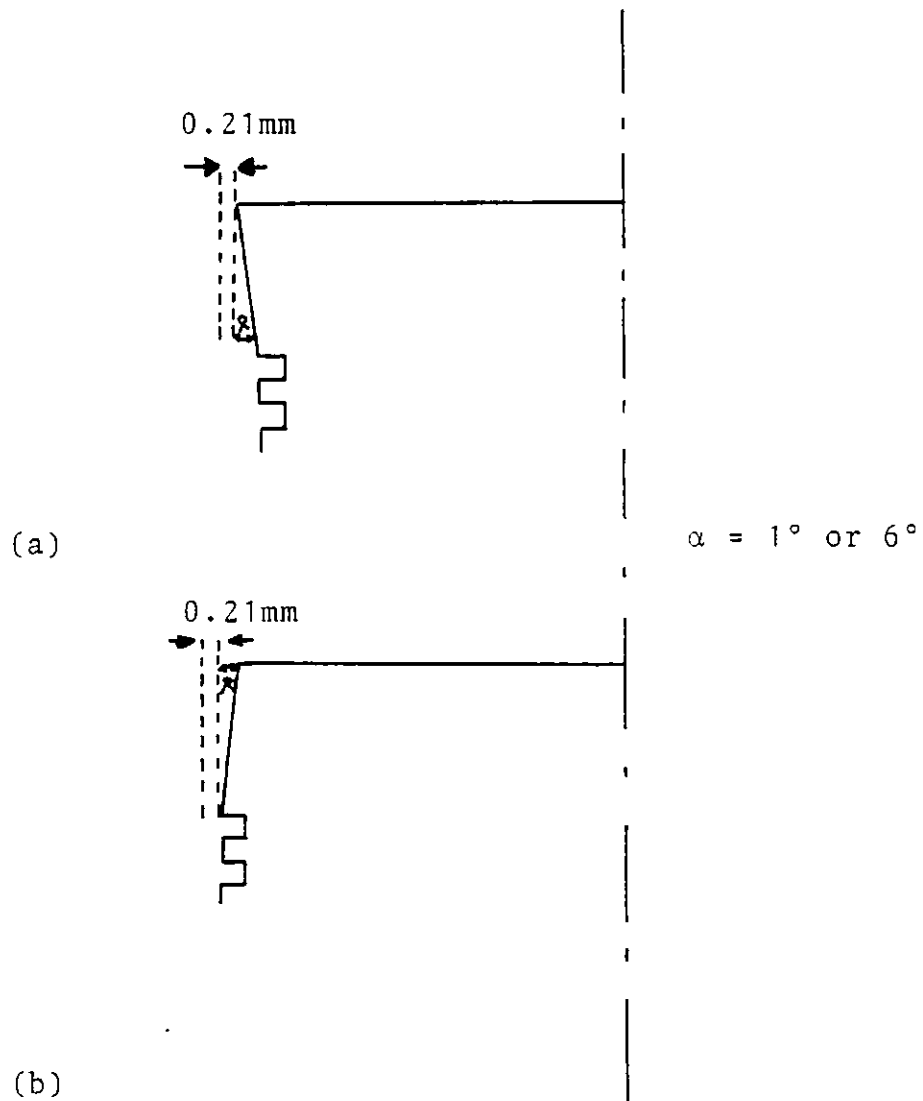


FIGURE 1.5 Two Different Crown Land Profiles

Furuhamma and Hiruma (43). The piston was slightly offset and an increase in oil consumption noted. This effect was also noticed by Wilson and Calow (33) and considered to effect bore polishing.

The cylinder liner surface finish has an effect on the performance of the liner. Willn and Brett (44) mention that diamond honed finishes usually give a poor performance when compared with silicon carbide honed finishes. They attribute this difference to loosely adhering flakes of liner material formed during the diamond honing process which act as an abrasive contaminant. Wilson and Calow (33) observed that the depth of the cross hatching was particularly relevant in engine tests.

The effect of the lubricant and its additives has received little attention with reference to bore polishing. Parsons (37) states that, by careful choice of oils and additives, bore polishing may be alleviated, although he concludes that the mechanisms involved are yet unknown. Schmidt and Michael (45) report upon tests with a 6 cylinder turbocharged diesel in which multigrade oils showed slightly lower liner wear than SAE 30 oils at load levels typically found in field use.

The formation of soot in a diesel engine can seriously affect the properties of the oil as well as form abrasive deposits on the crown land of the piston.

Rounds (46) states that above soot concentration of 3.5% the antiwear properties of zinc dithiophosphate (ZDP) are completely destroyed. McGeehan (47) observed that carbonaceous deposits on pistons taken from a Mack-5 turbocharged diesel lubricant test device contained 20% soot and the remainder being derived from the lubricant. By reducing the soot level bore polishing could be partly alleviated, although legislation in many parts of the world complicate this aim, since greater engine efficiency has a number of environmental drawbacks, i.e. pollution. Cloud and Blackwood (48) state that the major diesel fuel constituent governing wear is sulphur content. Their tests indicate that an increase of sulphur content from 0.2% to 1% (volume) can result in a two to sixfold increase in liner wear. Diesel fuel sulphur content is obviously one method of reducing the bore polish phenomenon, by a reduction in sulphur content.

Scott et al (12) describe an approach to the prevention and minimisation of scuffing which uses a surface coating on the piston rings. To assist with running-in some piston rings are tin plated to promote rapid seating. Ting and Mayer (49) also note that the piston ring profile has a great influence on oil film thickness and thus bore wear.

In conclusion, bore polishing may be alleviated in several ways :-

Piston crown land profile

Cylinder liner surface finish.

Soot concentration and fuel additives.

Lubricant and additives.

Piston ring profile and coatings.

#### 1.3.5 Research into bore polishing

Knight and Weiser (30) reviewed the suitability of existing test procedures for European automotive needs. They recognised the necessity for the development of a specific test method which could evaluate bore polishing. The Paramins Report (20) reviews single cylinder engines such as the Caterpillar 1-G and the Petter AVB and multicylinder engines such as the Volvo TD120 and Ford Tornado with reference to a possible bore polishing test. The conclusion was that single cylinder engines had poor reproducibility and were consequently abandoned whilst the turbocharged Ford Tornado differentiated well between two reference oils, based on field experience. The Ford Tornado was tentatively adopted by the Coordinating Engineering Council (CEC) as a standard industrial test. A full description of the operating procedure is described by the CEC Group (50)

Wilson and Calow (33) conducted bore polishing tests on a range of engines and stated that the single cylinder Caterpillar 1Y73 showed promise as a standard test since it differentiated well between reference oils,



although its repeatability was not fully acceptable. Shmidt and Michael (45) describe tests with a 6 cylinder turbocharged diesel in which the range of performance of several commercial oils was investigated in terms of piston deposits and liner wear. Bore polishing was not considered in these tests.

There was no evidence in the literature of a bench test which could simulate bore polishing. Mills and Cameron (27) describe the essential requirements of a bench test for investigation of boundary lubrication. These have been summarised on Page (30). A useful technique for the analysis of bore polishing in bench tests is the measurement of contact resistance as described by Furey (51). He reports that, in general, surface damage is more closely related to metallic contact than to friction. Courtney-Pratt and Tudor (52) found that at potential differences between 0.2 and 0.3 volts, electrical discharge could occur. Consequently, Chu and Cameron (53) used a 15 mV potential difference in a 4 ball test machine and defined the fraction of time spent at zero voltage as the percentage metallic contact. They also observed that the percentage metallic contact could be apparently influenced by the value of the resistors used in the potential divider circuit described by Furey (51).

#### 1.3.6 Conclusions of literature survey

Bore polishing is a phenomenon often encountered in

turbocharged diesel engines and also engines of long life. The characterisation is by a mirror-like appearance on the liner surface and the effects are increased oil consumption, blow-by and finally seizure. Very little is known of the mechanism of bore polishing although several important factors have been highlighted.

Research into bore polishing has taken place almost solely inside industry, and a variety of single cylinder and multi-cylinder diesel tests have been conducted in the search for a standard test method. The Ford Tornado has emerged as the standard industrial test method. The establishment of a reliable bench test to investigate bore polishing and compare lubricants for level of bore polishing has not been reported in the literature. This is despite the high cost of running a test in a Ford Tornado engine. There are numerous reports of bench test methods for investigation into piston ring scuffing and in many cases correlation with engine tests has been good.

Bore polishing and cylinder wear has been alleviated by a number of methods, and these have been highlighted. There is no conclusive evidence in the literature of any factor which either causes or reduces bore polishing to a much greater extent than any other factors. The mechanism of bore polishing can be seen to be complex.

There is clearly a need for increased research into

the mechanism of bore polishing, which is a serious problem encountered in many large, especially commercial, turbocharged diesel engines. The role of the lubricant and its additives needs increased attention and finally a relatively cheap bench test for bore polishing would prove of immense benefit as a lubricant screening device.

#### 1.4 OUTLINE OF PROJECT

As mentioned in the previous section there is no evidence in the literature of a bench test which can adequately simulate bore polishing. This has hindered the development of our understanding of bore polishing since it has meant that the phenomenon can only be studied in expensive and lengthy engine tests.

This thesis describes an attempt to alleviate this deficiency. It describes the development of a simple test rig which produces a phenomenon similar to bore polishing observed in engines (Chapters 2 and 3). The thesis then attempts to correlate this rig with engine tests by a series of tests on a set of commercial oils of previously defined bore polish percentage (Chapter 4). Finally in Chapter 5 a more closely controlled set of lubricants were used to investigate the effect of ZDDP antiwear additive concentration upon bore polishing.

C H A P T E R 2

Apparatus

## 2.1 INTRODUCTION

### 2.1.1 Background

The establishment of the H.F.R. apparatus described by Mills and Cameron (27) and Mills (28) and subsequently improved by Shimauchi (29) provided a method by which piston ring lubrication, particularly at T.D.C. could be investigated. The H.F.R. apparatus was readily adaptable to the geometry of piston ring and cylinder liner interaction. Sections 2.2 and 2.3 detail the modifications made in the development of a new H.F.R. apparatus, whilst this section reviews previous work with the H.F.R. apparatus.

Mills (28) used the H.F.R. apparatus to investigate the lubrication of steel by a simple sulphur E.P. additive, dibenzylidisedisulphide (DBDS) and also fatty acids. He also investigated the lubrication of chromium plated piston rings and cast iron cylinder liners with three base stocks and a commercial E.P. additive. In this last investigation, he reports observing bore polishing and plastic deformation and draws some important conclusions about the lubrication of steel by base stocks. He used a 1% (weight) commercial E.P. additive (zinc dialkyldithiophosphate [ZDDP]), and deduced some properties of the additive, but did not extend this by considering variable concentrations of additive. Mills also considered the effect of surface finish by conducting tests with liner specimens which had been diamond honed and liners which had been silicon carbide honed. He reports observing very

little difference between the two types and suggests that surface finish affects only the generation and sustainment of a hydrodynamic oil film and not a boundary oil film, provided frictional heating remains insignificant.

Shimauchi (29) used the H.F.R. apparatus to investigate the boundary between the three lubrication regimes by considering the lubrication of piston ring and liner as well as ball bearing on EN31 steel specimens. He used a base stock for these tests, and found that the investigation of boundary to mixed lubrication regimes gave poor repeatability. Nearly all the previous work conducted with the H.F.R. apparatus has shown it to be a reliable, repeatable and useful method of investigating piston ring and cylinder liner lubrication. There has, however, been no comparison made between the results of the H.F.R. apparatus with actual engine tests. It is hoped to remedy this deficiency in the following pages.

### 2.1.2 General Description

The apparatus was designed in order to simulate the conditions at T.D.C. in a diesel engine. A pure lubrication system has been adopted, with no combustion products present. Essentially, the apparatus consists of a section of scraper ring and holder which is loaded against a section of cylinder liner. These are shown on page 54 situated to the right of the vibrator. The stainless steel holder is then oscillated by an electric vibrator at a frequency of 50Hz and an amplitude of  $\pm 1$ mm. The amplitude is small so that

1. Boundary lubrication is maintained.
2. Frictional heating is minimised.

The 'flash' temperature was calculated by Mills (28) and found to be 5.75°C, indicating that frictional heating in the context of this study is negligible. The piston ring and cylinder liner are placed in an oil bath, which is itself situated in an aluminium heating block.

## 2.2 MECHANICAL APPARATUS

A schematic diagram of the apparatus is shown in Figure 2.1. The basic design of the apparatus is described by Shimauchi (29) and there follows a description of the modifications made to the original apparatus.

### 2.2.1 Load carrier

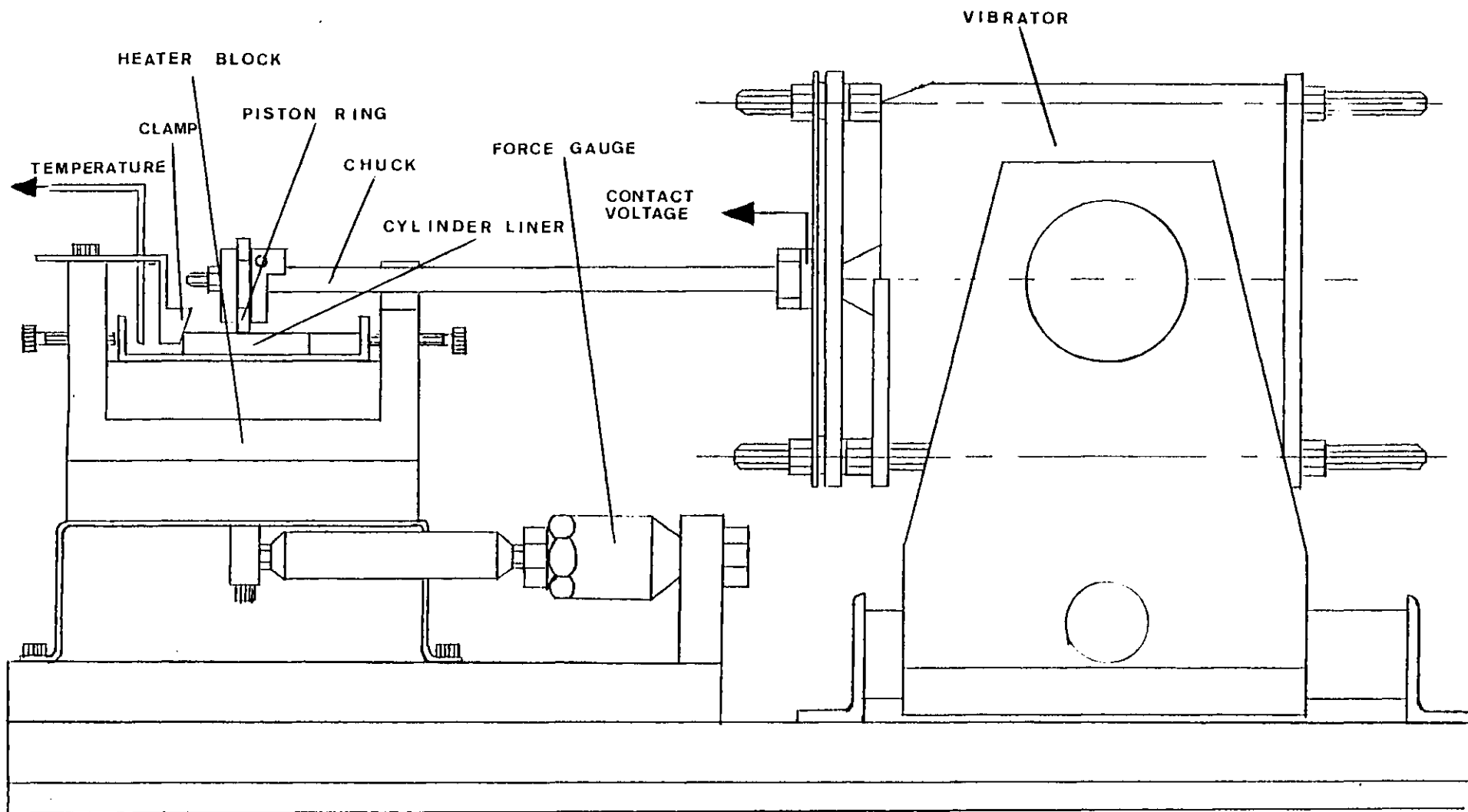
As in the previous design the load is applied by dead-weight. The method of application has been redesigned to minimise vibration previously encountered by this deadweight. Figure 2.2 shows a front view sketch of the new loading system. The new design incorporates a spring which helps to cut down vibrations encountered by the piston ring holder.

### 2.2.2 Clamping system

It is essential that the liner specimen is rigidly clamped for the duration of the test, since any movement will be detected by the force gauge, producing spurious data.

Furthermore, in order for the wear scar to be properly

FIG 2-1 SCHEMATIC DIAGRAM OF APPARATUS





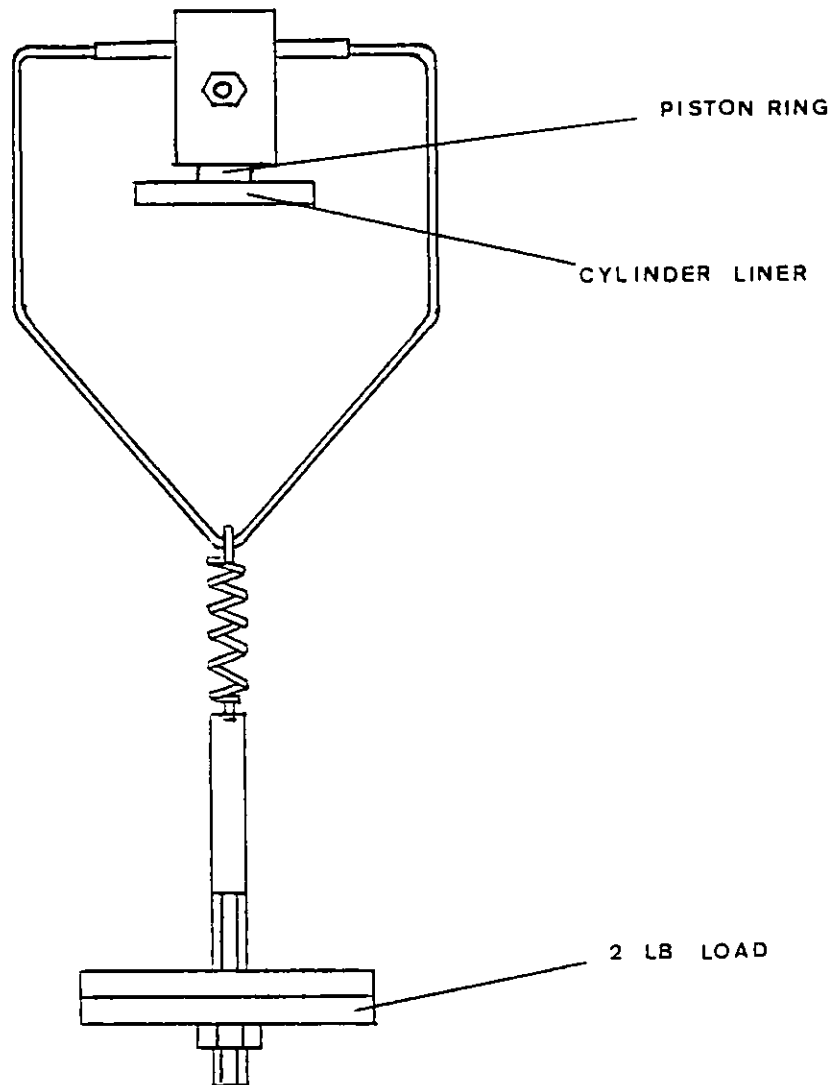


FIG 2-2 FRONT VIEW OF LOADING SYSTEM

established, the liner must not be allowed to move relative to the oil bath. In the new apparatus the liner is pushed against a spacer located in the oil bath by tightening the clamp screw.

#### 2.2.3 Oil bath

Two oil baths were designed for the new apparatus. The first was similar to that used by Shimauchi (29). In addition, an oil bath was designed with a downspout which would allow for oil drainage and collection. A 5mm diameter hole was made through the heating block and asbestos insulation to accommodate this oil bath.

#### 2.2.4 Base plate

In order to reduce the vibrations found in the previous design a thick base plate was used. This was then mounted on a thick layer of cork matting.

#### 2.2.5 Base structure

The photograph on Page (54) shows a side view of the apparatus which is mounted on a base structure. This framework was incorporated for the following reasons:-

- 1) To allow the deadweight to hang freely. In the previous design it was necessary for the load to be hung over the end of the bench.

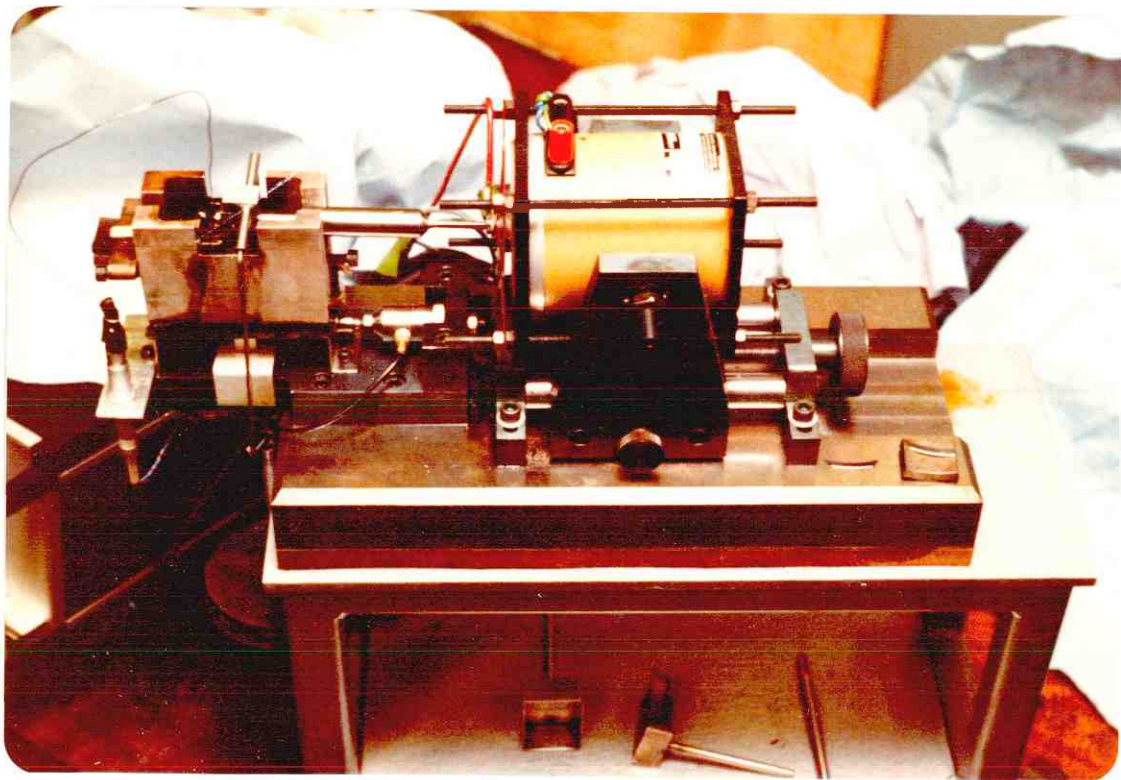


Figure 2.3 View of Mechanical Apparatus

2) The framework has four retractable feet.  
This enables the entire apparatus to be inclined up to  $15^{\circ}$ .

3) To lend further rigidity to the apparatus and hence reduce the vibrations transmitted to the force gauge.

### 2.3 Electrical apparatus

The electrical apparatus was designed and made by Mr. P. Bonner of Micoware Computer Systems Ltd., based upon provided specifications. The circuit diagrams are included in the thesis, Page (257-267) and there follows a brief description of the functions carried out by the apparatus.

#### 2.3.1 Oscillator

This unit controls the frequency and power fed to the vibrator. The frequency range is 5 - 200 Hz. The power fed to the vibrator is controlled through the set level dial found on the front control panel (see page 267 ). This dial controls the stroke length of the piston ring and has a maximum unblown stroke length of  $3\frac{1}{2}$ mm. The frequency of the vibrator is indicated on a three digit display. Details of the main amplifier are given on Page 56 The amplifier was supplied by I.L.P. Electronics Ltd., of Canterbury, Kent.

| Module Type | Output Power                       | Load Impedance  | Input Sensitivity and impedance  | Distortion                  | Signal to Noise ratio | Frequency response             | Power Supply Voltage |
|-------------|------------------------------------|-----------------|----------------------------------|-----------------------------|-----------------------|--------------------------------|----------------------|
| HY200       | 120 W<br>RMS<br>into<br>4 $\Omega$ | 4 - 16 $\Omega$ | 500 mV RMS<br>into 100K $\Omega$ | 0.01%<br>typical<br>at 1KHz | 100 d B<br>minimum    | 10 Hz to<br>45 KHz -<br>3 d B. | -45:0:+45            |

TABLE 2.1 MAIN AMPLIFIER DATA

### 2.3.2 Force amplifier

The friction force between piston ring and cylinder liner is monitored by a piezoelectric crystal force gauge.

Details of the gauge are given below.

| TYPE                            | IMPEDANCE HEAD<br>TYPE 8001 |
|---------------------------------|-----------------------------|
| Manufacturer                    | Brüel and Kjaer             |
| Force gauge voltage sensitivity | 384 mV/N                    |
| Force gauge charge sensitivity  | 382 pC/N                    |
| Stiffness below accelerometer   | $25 \times 10^5$ N/M        |
| Force gauge capacitance         | 995 pF                      |

TABLE 2.2 FORCE GAUGE DATA

The output from the force gauge is fed into a charge amplifier and then displayed on an oscilloscope. The output from the charge amplifier is also rectified and relayed to a chart recorder. The photograph on Page 84 shows a typical oscilloscope trace. The upper trace is friction force, whilst the lower trace is contact voltage.

### 2.3.3 Thermocouple amplifier

Details of the thermocouple used are given below:

| LENGTH | DIAMETER | CONDUCTOR | TYPE NUMBER       |
|--------|----------|-----------|-------------------|
| 300mm  | 0.5mm    | NCr/NA1   | 05-FKSN<br>300 ZA |

TABLE 2.3 THERMOCOUPLE DATA

The Thermocouple was supplied by Universal Thermosensor Ltd., Kent.

The output from the thermocouple is then amplified and displayed on a three digit display on the front panel of the apparatus. The amplifier has a cold junction compensation.

### 2.3.4 Temperature controller

This unit has several functions.

#### a) Rate

At the start of each test the required heating rate may be selected between 1°C rise per minute up to 100°C rise per minute. This value is controlled using the set buttons when the selector is in the 'Rate' position, shown on Page (267).

b) Final temperature

At the start of each test the final required temperature is fixed using the set buttons when the selector is in the 'Final' position.

During the test the temperature controller follows the ramp between initial and required temperatures at the desired rate. The temperature controller is connected to two 200W cartridge heaters which are located in the heating block. Details of the heaters are given below.

| POWER | VOLTAGE | LENGTH | DIAMETER |
|-------|---------|--------|----------|
| 200W  | 240V    | 62mm   | 6mm      |

TABLE 2.4 DATA ON CARTRIDGE HEATERS

2.3.4.1 Ramp temperature display

The value of the temperature which the controller is attempting to reach is displayed when the selector is in the 'Ramp' position.

2.3.4.2 Oil temperature display

The value of the bulk oil temperature is displayed on this gauge. The heaters are controlled



according to the relationship between this temperature and the ramp temperature.

The heaters are only operative when the selector switch is in the 'Display Temp' or 'Display Ramp' positions. This allows the electronics to be set without the heaters being operative.

#### 2.3.5 Constant voltage source

In order to obtain an indication of the oil film thickness between piston ring and cylinder liner, it was decided that a 16 mV potential should be applied between the two components. The potential between the contact is monitored and OV was taken to indicate metal contact, whereas 16 mV indicated a thick oil film. A photograph of the typical display from the oscilloscope is shown on Page(84) The lower trace is the voltage across the contact, whilst the upper trace is friction force output.

#### 2.3.6 Potential divider

A potential divider with a 1000 $\Omega$  logarithmic potentiometer was designed to make an estimate of the contact resistance. This would give some indication of relative film thicknesses. With a voltage drop of 8 mV across the logarithmic potentiometer the resistance of the contact must be the same as the resistance of the potentiometer.

In this way the resistance of the contact may be found between  $10\Omega$  and  $1000\Omega$ .

#### 2.3.7 Displacement

A displacement transducer is incorporated in the apparatus. Details of the transducer are given below.

| Model            | Linearity<br>on<br>Calibration | Calibration<br>Temperature | Calibration<br>Load | Sensitivity                      |
|------------------|--------------------------------|----------------------------|---------------------|----------------------------------|
| D5/<br>100<br>AG | $\pm 0.3\%$                    | $18^{\circ}\text{C}$       | $100\text{K}\Omega$ | $2.13 \text{ mV}/\text{V}/0.001$ |

TABLE 2.5 DISPLACEMENT GAUGE DATA

The transducer was supplied by RDP Electronics, Wolverhampton.

A sketch of the output of the transducer against displacement is shown on Page (65). This device was used to monitor the stroke length of the piston ring at intervals throughout each test.

#### 2.3.8 Power supply unit

The function of this unit is to provide low voltage sources which are needed to power the

electronic circuits of the apparatus. In this respect 5V, 15V and 30V sources are required.

## 2.4 Apparatus calibration

### 2.4.1 Contact resistance

Figure (2.6) shows the circuit used in order to obtain a plot of contact resistance against contact voltage for two values of potentiometer resistance.

Known resistors,  $R_1$ , were placed between the piston ring and cylinder liner and the corresponding voltage drop noted. Readings were taken for potentiometer values of  $100\Omega$  and  $1000\Omega$  since these would relate to a thin oil film and a thick oil film respectively. It was intended that a plot of film thickness against contact resistance would be made in order to establish a film thickness/contact voltage graph, however no method was devised for measuring film thickness. The plot shown on Page (70) enables the contact resistance to be ascertained once the contact voltage is known, for the  $100\Omega$  and  $1000\Omega$  settings of the potentiometer.

### 2.4.2 Displacement

The displacement gauge was clamped to the oil bath and readings were taken from the digital display of the electrical apparatus. The frequency was 50 Hz,

as this was the frequency used during each test. The graph on Page (65) shows the output of the gauge for various loads, the set level corresponds to the power level fed to the vibrator.

By using a scale slip, as employed by Shimauchi (29) the actual stroke length was determined as a function of displacement gauge readings. The scale slip was attached to the chuck and the values of stroke lengths up to 2mm were noted in terms of gauge output. The procedure of measuring stroke length with the slip is described by Shimauchi (29).

By using the graph on Page (65) and the data obtained using the scale slip a final plot of stroke length against set level was obtained. This is shown on Page (64). Using this method it was found that 1mm stroke length at 50 Hz corresponds to a set level of 28 units.

#### 2.4.3 Coefficient of friction

##### 2.4.3.1 Normal load

The normal load at the contact is composed of three factors.

##### a) Deadweight

The deadweight used in all tests was 21b mass.

Fig 2.4 STROKE LENGTH v SET LEVEL AT 50 Hz FOR DISPLACEMENT GAUGE.

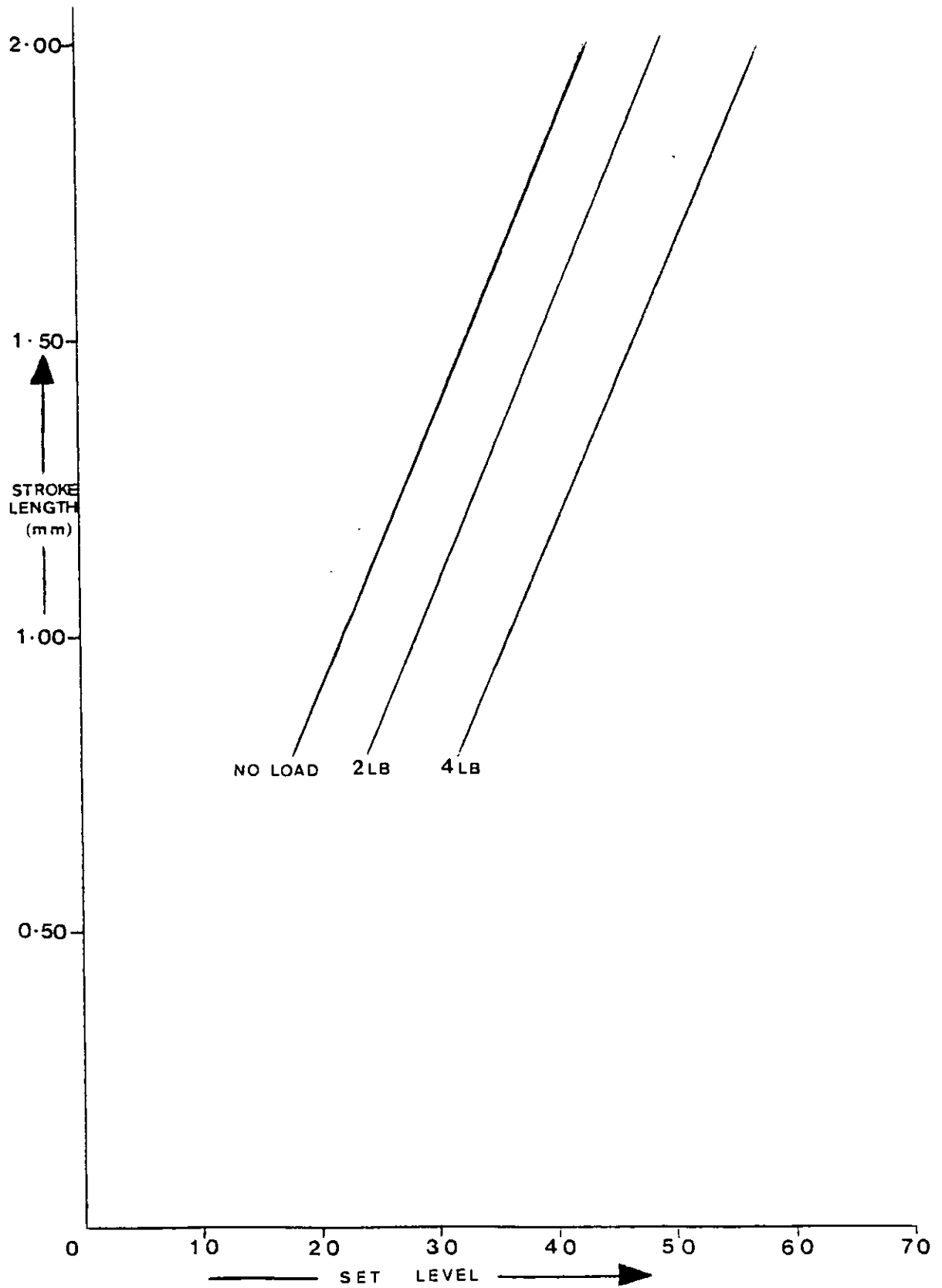
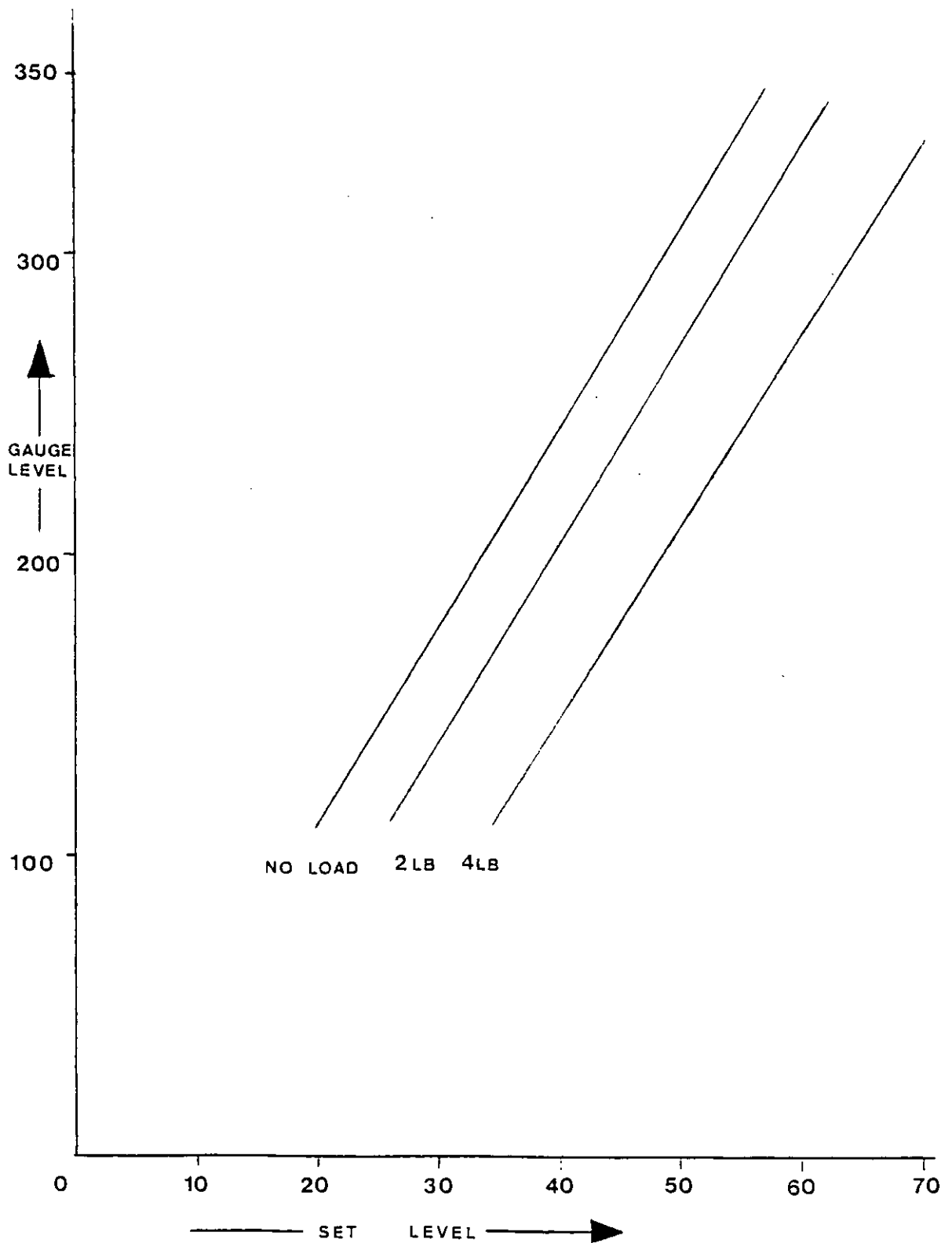


Fig 2-5 GAUGE LEVEL v SET LEVEL AT 50 Hz FOR DISPLACEMENT GAUGE.



This approximates to a contact pressure of  $37 \text{ MN/M}^2$ , which is somewhat higher than cylinder pressures found in turbocharged diesel engines. This higher pressure was employed to cut testing time down and was not considered to prejudice the results obtained.

b) Deadweight carrier

As can be seen on Page (52) the deadweight is attached to the chuck with a carrier. The total mass of carrier was found to be 29 grammes.

c) Chuck force

Without any deadweight or carrier there is a downward force on the contact due to the mass of the chuck. By using the axis of the vibrator as a convenient pivot a set of counterbalancing weights was added to the studs at the back of the vibrator. Weights were added until the piston ring just left contact with the liner. This was achieved using the contact voltage apparatus. By equating moments about the axis of the vibrator the downward force was found. This value was confirmed using a spring gauge to separate the contact.

The downward force was found to be 38.5gf.

Hence the total downward force, when horizontal,  
was found to be

$$\left( \frac{2}{2.2} \times 1000 + 38.5 + 29 \right) \text{gf}$$

$$= 9.57\text{N}$$

#### 2.4.3.2 Calibration

The apparatus was calibrated using the method described by Mills (28). Essentially, a known charge was applied to the input of the charge amplifier and the deflection of the pen recorder noted. This charge was made to correspond to a normal load of 9.57N and coefficient of friction of 0.1.

Hence if  $\mu = 0.1$ , Friction force = 0.96N  
from Page (57) Charge Sensitivity = 382 pC/N.  
Thus a charge of 367 pC will correspond to a friction coefficient of 0.1.

The deflection was found to be 5cm/  
0.1 friction  
coefficient.

#### 2.5 Recording apparatus

The data from the tests was analysed in  
two ways.



i) The output from the charge amplifier was displayed on an oscilloscope. The voltage detected between the piston ring and cylinder liner was also displayed on the oscilloscope.

ii) The friction force output from the charge amplifier was rectified and fed to a chart recorder. The contact voltage was also relayed to the chart recorder.

These methods are discussed in Chapter three

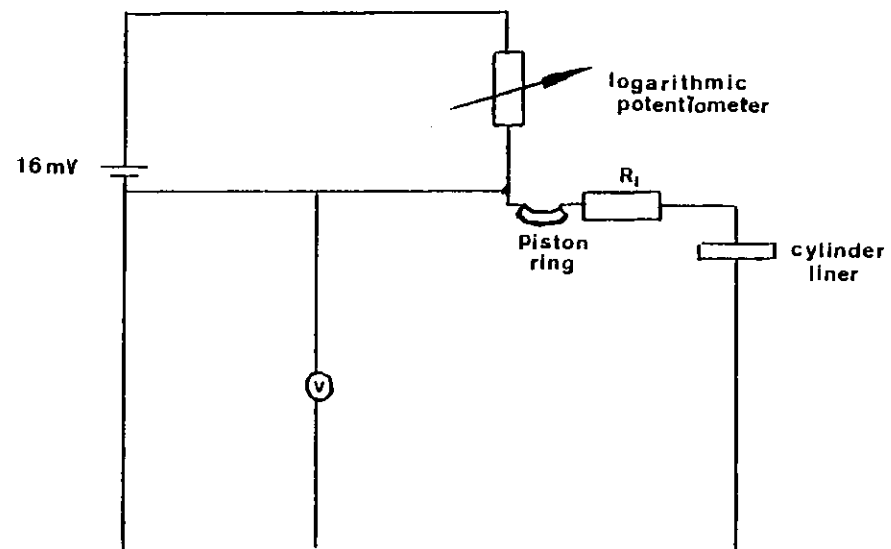
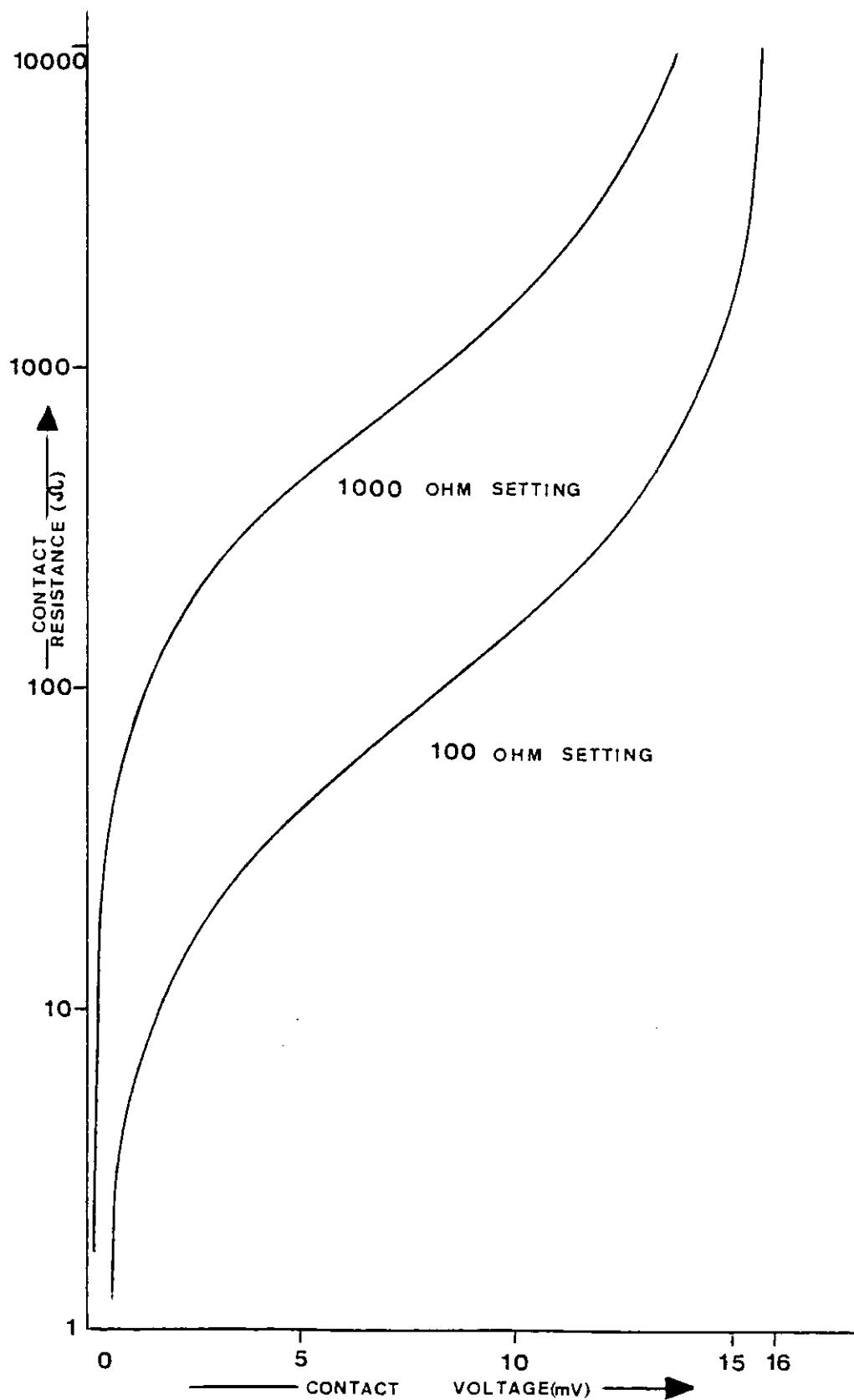


Fig 2-6 Calibration of contact resistance circuit

Fig 2-7 CONTACT RESISTANCE CALIBRATION



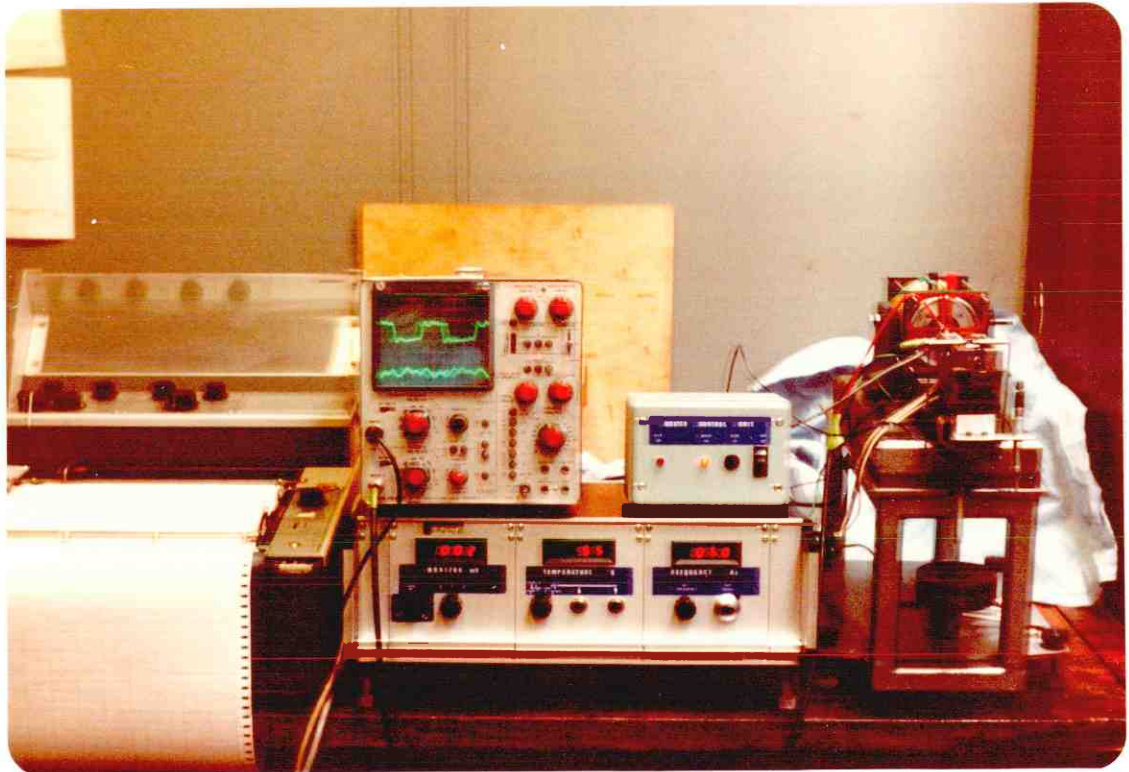


Figure 2.8 Overall View of Apparatus

C H A P T E R 3

Preliminary Results

## CHAPTER 3

### Preliminary Results

#### 3.1 Operating conditions

This section describes the experimental conditions of each of the tests detailed in this thesis. The various parameters associated with the running of these tests are briefly discussed.

##### 3.1.1 Temperature range

The temperature of the piston ring at top dead centre (T.D.C.) is influenced by a great many factors. Hamilton and Moore (13) found, using a Petter AV1 single cylinder diesel at maximum power output, the T.D.C. liner temperature was  $246^{\circ}\text{C}$ . McGeehan (47) confirms that typical oil film temperatures at T.D.C. are of this order. The actual piston crown land temperature is much higher. McGeehan (14) indicates that temperatures are in the range  $300-350^{\circ}\text{C}$ .

It was decided that the tests would be carried out at three temperatures to cover the range of piston ring temperatures found in the literature. These were  $200^{\circ}\text{C}$ ,  $250^{\circ}\text{C}$ ,  $300^{\circ}\text{C}$ .

##### 3.1.2 Time duration

In order to determine a suitable duration for the tests described in this thesis, a number of experiments were conducted with the apparatus run at room temperatures with a mineral oil base stock. The experiments were run for periods between 30 minutes and 3 hours. The conclusion reached was that a minimum of 1 hour was required to produce a clearly defined wear scar. It was decided that the duration of the tests should be 2 hours to ensure the formation of the wear scar. Two hours were found to be necessary for a wear scar at 200°C and 250°C.

At test temperatures in excess of 250°C it was discovered that the oil boiled off at such a rate that the piston ring and cylinder liner contact was not covered for the 2 hours the test lasted. As a result of this observation it was decided to run tests over 250°C for 1 hour whilst tests up to, and including 250°C, should be run over 2 hours. This is described in greater detail in section 3.5.4.

The effect of conducting the tests for two different time intervals is not significant, since the most important information gained from the experimental work was found by a comparison of different oils at the same temperature and hence the same conditions.

### 3.1.3 Temperature rise rate

The rate at which the oil temperature is

increased is significant. If the rate is too fast, then the contact temperature will be lower than the bulk oil temperature and the piston ring will be at a lower temperature than that of the liner. This would lead to inaccuracies in the temperature recording since the thermocouple was immersed in the bulk oil. If the rate is too slow, the oil is more likely to oxidise and furthermore, for 1 hour tests the maximum temperature would not be achieved. Mills (28) in a similar manner found that there was a  $1.5^{\circ}\text{C}$  temperature difference between the piston ring and liner for a temperature rise rate of  $7^{\circ}\text{C}/\text{minute}$ . This heating rate was used in all the tests since  $1.5^{\circ}\text{C}$  was considered negligible in comparison to bulk oil temperatures.

#### 3.1.4 Frequency

The value of the frequency used in all the tests was 50 Hz. This frequency was used by Mills (28) and also Shimauchi (29) and corresponds to 3000 r.p.m. which is slightly higher than repetition rates found in actual working diesel engines.

#### 3.1.5 Load

The contact area between ring and liner was estimated from the wear scar when a 21b load was used. The measured contact area was  $0.24\text{mm}^2$ ,



giving a contact pressure of  $37 \text{ MN/m}^2$ . This load gave a satisfactory wear scar. The pressure of  $37 \text{ MN/m}^2$ , although higher than ring pressures in diesel engines, was still much lower than the yield stress of the cast iron material and was not considered to be unrealistic. It was used to reduce test duration.

#### 3.1.6 Stroke length

Previous work by Mills (28) and Shimauchi (29) has shown that the stroke length must be small in order to minimise frictional heating and to keep mid-stroke sliding speeds low. The conclusion from their work was that a total stroke length of 1 mm was the maximum value of stroke length for boundary lubrication still to occur. This value was adopted for all the tests conducted.

#### 3.1.7 Contact voltage

The method of using a potential difference across the friction pair metallic contact is based upon the circuit designed by Furey (51). A low value of potential difference is used since it was found by Courtney-Pratt and Tudor (52) that electrical discharge could occur at voltages of 0.2V to 0.3V. The potential difference was chosen as 16 mV.

### 3.1.8 Logarithmic potentiometer value

As described on Page (60) the contact voltage circuit has a logarithmic potentiometer incorporated in it which has the range  $10\Omega$  to  $1000\Omega$ . By selecting a value on the logarithmic potentiometer the resistance of the contact may be compared with this pre-set resistance. As a consequence, the oil film resistance may appear to vary as a function of logarithmic potentiometer resistance as described by Chu and Cameron (53). A value of  $100\Omega$  was used since this was found sufficient to describe the build-up of an oil film at low resistance, and also at higher resistance.

It was noticed in many tests that the contact voltage increased, implying a separation of piston ring and liner by some form of surface film. By stopping the test suddenly, the contact voltage was seen to drop down to zero immediately. This suggested that there was no varnish present on the surface. Furthermore, if the stroke length was increased during the test so that new liner was rubbed, it was noticed that initially no oil film was detected. The oil film would slowly build up, implying that the effect was a contact region phenomenon. The film was clearly not a varnish and was called a 'thick boundary oil film'. Its thickness was estimated to be of the order of  $1000\text{\AA}$  (28) .

### 3.2 MATERIALS

#### 3.2.1 Piston Rings and Cylinder Liners

##### a) Metallurgy

The material used in diesel engine rings/liners is invariably grey flake cast iron of A.S.T.M. type 'A'. The main reasons for its use are cheapness and ease of machining, its ability to make good casting impressions, wear resistance and low melting temperature (54).

Cast iron contains a high quantity of carbon (typically 2-4%) and frequently high silicon. The carbon exists in the form of graphite (stable) and cementite (unstable). The graphite itself may be either flake or spheroidal in structure. Spheroidal graphite enhances the ductility of the cast iron and is sometimes used in high speed diesel engines. The precise microstructure is controlled by the carbon equivalent value (below) as well as cooling rate, alloying additions and thickness of the particular section.

$$\text{C.E.V.} = \%C + \frac{\% (P + Si)}{3}$$

For a given C.E.V. and bar diameter the structure of the cast iron may be determined (6). It is important to maintain free ferrite levels in the cast iron to below 5% since the ferrite makes the cast iron soft, weak and prone to scuffing.

Most cast irons contain phosphorus since this renders the metal very fluid in the molten stage.

The type of cast iron used in liner material is invariably pearlitic cast iron since this is machinable and has high strength.

b) Surface finish

The two most common surface finish techniques for diesel liners are diamond honing and silicon carbide honing. Diamond honing produces a torn and folded surface which can cause metal to metal contact and particle detachment. The silicon carbide honing technique is employed by the great majority of engine producers and often has a surface finish of 20-40 $\mu$  in centre line average (CLA), since this gives good oil retention properties and aids longer life.

Piston rings are usually chromium plated and require lapping to produce an acceptable profile, care being taken to ensure that the plating has no sharp edges which cause undesirable edge loadings during running-in.

The cylinder liner segments used in the study were cut from a commercial liner of 89mm bore and were of flake graphite cast iron metallurgy of A.S.T.M. classification type 'A'. The segments were 20mm x 20mm in dimension, and had been silicon carbide honed.

The piston rings used had the same metallurgy as top compression rings and were in 15mm segments from one of the oil control rings of a diesel engine of 76mm bore. The

rings had an axial thickness of 0.3mm which ensured that in a 1mm amplitude fresh metal was completely uncovered on each stroke and fretting would not occur. The piston rings were of a smaller diameter than the liner segments in order to eliminate edge contact. A new pair was used for each test.

For more information on the subject of cast iron metallurgy the reader is referred to Rollason (54).

### 3.2.2 Lubricant and Additives

There are two distinct types of lubricant used:

#### a) Fully formulated commercial oils

A set of 6 fully formulated commercial oils of bore polishing percentage characterised by the Ford Tornado were used. The results are discussed in Chapter 4, and details of the oils are given below.

| OIL | SAE<br>VISCOSITY<br>GRADE | SULPHATE<br>ASH<br>CONTENT | MAJOR<br>ELEMENTS | API<br>DESIGNATION | BORE<br>POLISH<br>% |
|-----|---------------------------|----------------------------|-------------------|--------------------|---------------------|
| C1  | 20W-40                    | 1.8                        | Zn,P,Ca           | SD/CD              | 17                  |
| C2  | 20                        | 0.95                       | Zn,P,Ca           | SD/CD              | 45                  |
| C3  | 30                        | 1.95                       | Zn,P,Ca           | SD/CD              | 15                  |
| C4  | 30                        | 1.0                        | Zn,P,Ca,Mg        | SE/CD              | 55                  |
| C5  | 15W-40                    | 1.4                        | Zn,P,Ca,Mg        | SE/CD              | 20                  |
| C6  | 30                        | 1.4                        | Zn,P,Ca           | SD/CD              | 15                  |

TABLE 3.1 DETAILS OF COMMERCIAL OILS

#### b) Base stock and commercial additive

A mineral base stock was used which is

described by Mills (28) and corresponds to B2 in his test work. A commercial antiwear ZDDP material was added to the oil at a range of concentrations. The additive is described more fully by Mills (28). The results of these tests are discussed in Chapter 5.

### 3.2.3 Cleaning procedure

Before each test the oil bath, chuck, piston ring and holder, cylinder liner, clamp and spacers were cleaned in Toluene in an ultrasonic bath for 10-15 minutes. At the end of this they were then cleaned with acetone to remove traces of toluene and allowed to dry in air. The apparatus was then carefully assembled with a pair of tweezers, also cleaned in the above procedure, and the test started immediately afterwards to minimise contamination.

After every five tests, or after every high temperature test ( $300^{\circ}\text{C}$ ) the items listed above were boiled in a solution of water and sodium hydroxide for 40 minutes or until all the burnt oil had been removed. They were then washed in a continuous stream of running tap water for 40 minutes. After this they were dried with clean tissue paper and once again cleaned with toluene and acetone as

previously described.

The ring/liner specimens were cleaned in toluene and acetone when they had cooled down at the end of each test. This was necessary since it was found that oil, dust etc., were charged up by the scanning electron microscope causing the wear scar to be partially obscured.

### 3.3 Test Analysis

The test analysis was in five parts.

#### 3.3.1 Pen recording

A two channel Rikadenki chart recorder was used for all the tests. By setting the paper speed at 1cm/min it was possible to obtain a detailed record of the two inputs. The fine detail was not significant in the analysis. The two inputs were:

##### a) Friction force

As described in Chapter 2 a piezoelectric crystal force gauge was used to monitor the friction force at the contact. The output from the force gauge was relayed to a charge amplifier and rectifier and then to the chart recorder. From knowledge of the normal contact load the output from the chart recorder can be calibrated

to give friction coefficient. This is described on Page (67).

b) Contact voltage

The potential difference across the ring and liner segments was recorded by the second channel.

As described earlier, the potential difference across the contact is an indication of the percentage metallic contact between ring and liner segments. Zero voltage corresponds to total metallic contact whilst 16mV corresponds to a 'thick' boundary oil film with no metallic contact.

3.3.2 Oscilloscope

Again there were two inputs.

a) Friction force

The output from the charge amplifier was monitored throughout each test. The photograph on Page (84) illustrates a typical oscilloscope output. The friction force is the upper trace. The 'jagged' profile is due to slight vibrations of the apparatus, the frequency of which





Figure 3.1 View of Oscilloscope

corresponds to its natural frequency. These vibrations, although negligible, produce an undesirable affect on the oscilloscope output. This is mentioned again in Chapter 7.

#### b) Contact voltage

The photograph on page (84) illustrates a typical contact voltage output (lower trace). The voltage trace varies between 0V and 16mV across the contact, indicating that there is intermittent metallic contact. Chu and Cameron (53) used a similar circuit and defined the percentage metallic contact as the fraction of the time spend at 0V. This technique, however, has not been employed in the test analysis.

The oscilloscope was used as a visual aid to analysis only, no record of the oscilloscope was made continuously for each test.

### 3.3.3 Scanning electron microscope

#### a) Visual examination

After each batch of tests the liner specimens were cleaned in the manner detailed on page (81), and examined under a scanning electron microscope. Information was gained in three ways:

- 1) A visual examination of each liner surface enabled any correlation between bench test results and

engine test results to be obtained.

- 2) The visual examination enabled new light to be cast upon the possible mechanisms involved in bore polishing.
- 3) The effect of temperature upon bore polishing could be investigated by a visual comparison of the liner surfaces.

The piston rings were also observed under the S.E.M. but it was found that very little information could be gained from this study. The photograph on page (87) shows the contacting surface of the piston ring as seen on every ring observed. There is some evidence of cracking of the chromium plating and fine scratches in the sliding direction (left to right) but no evidence of scuffing as illustrated by Crooks (55) and many other authors. There was no evidence of deep scratching of the ring surfaces and this may be due to smoothening of the ring surfaces by running-in as described by Crooks (55).

The sketch on page (88) shows a simplified block diagram of an S.E.M.. Electrons from an emission source (filament) are accelerated by a potential, typically in the range of 1-30kV, and focussed onto the specimen by two or three magnetic lenses. Scanning coils cause the electron spot to be swept across the specimen surface. The currents passing in these scanning coils are made to pass through corresponding deflection coils of a cathode ray oscilloscope. This allows a larger image of the specimen to be seen on a viewing screen.



Figure 3.2(a) Unrun Piston Ring surface. (200x).

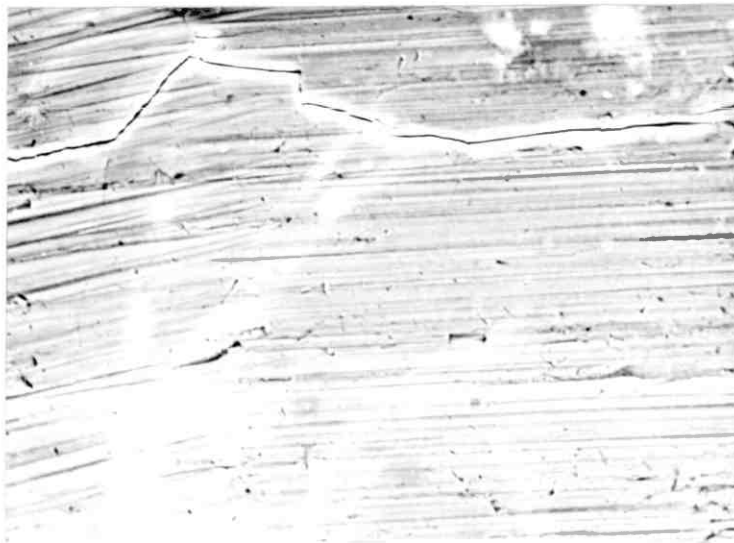


Figure 3.2(b) Tested Piston Ring surface. (200x).

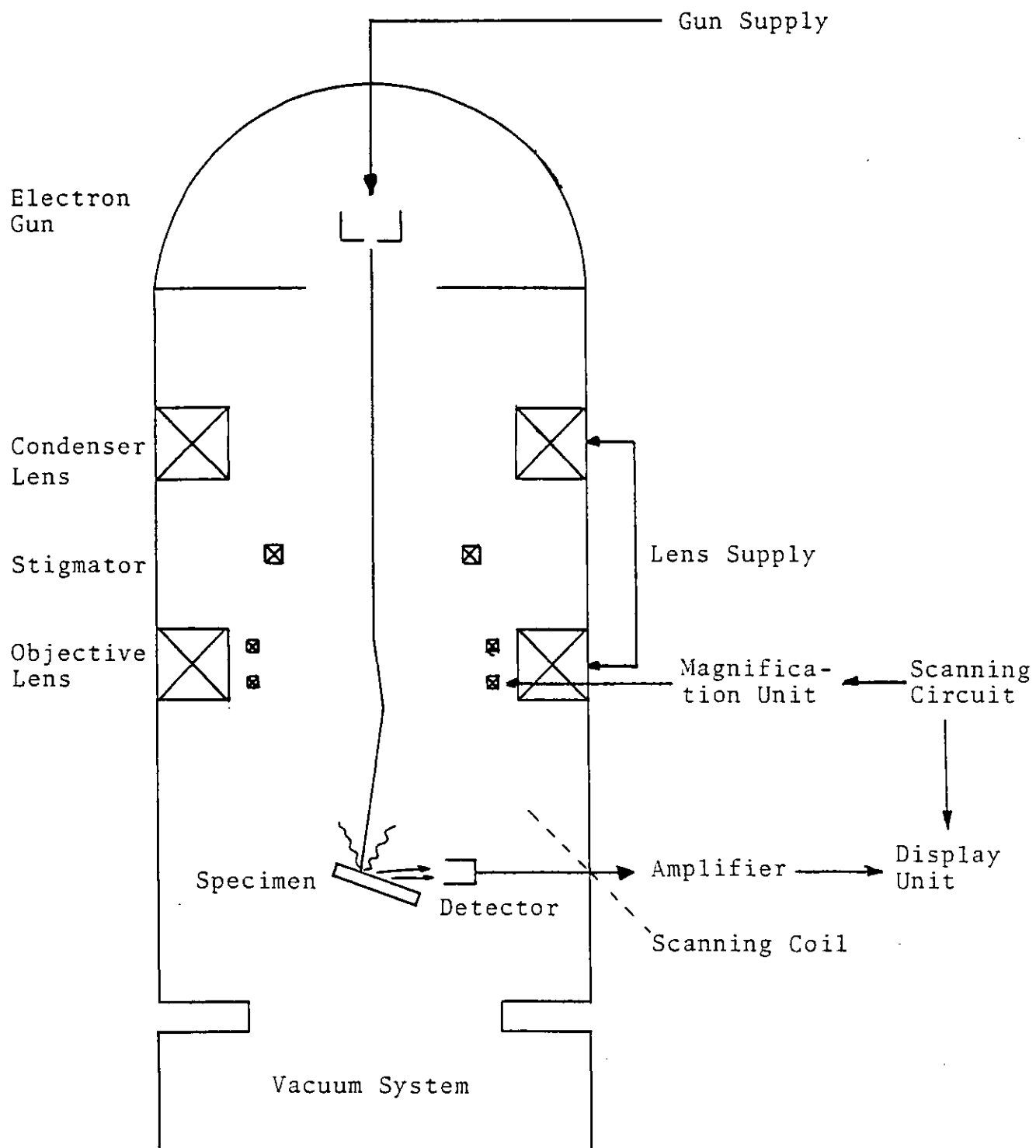


FIG 3-3 SIMPLIFIED SCHEMATIC OF AN SEM

Secondary electrons emitted from the surface of the specimen strike the collector and the resulting current is amplified and used to modulate image brightness on the cathode ray tube.

The S.E.M. has the advantage of a great range of magnifications, typically from 50 up to 50,000. In addition the S.E.M. has greater resolution when compared with optical microscopes. One important disadvantage is that non-metallic specimens must be made electro-conducting by plating techniques. For more details on the S.E.M. the reader is referred to the review by Buckley (56), and the book by Phillips(57).

#### b) Chemical analysis

Many scanning electron microscopes have the capability of elemental analysis of wear surfaces and debris by an energy dispersive X-ray analyser. This technique was used in the study for two reasons.

- 1) To investigate the chemistry of the worn surfaces of the liner specimens. It was hoped that this would lead to a greater understanding of the processes involved in bore polishing.
- 2) To determine the nature of wear debris collected from the oil samples by ferrography. It was important to determine whether debris was ferrous, oil degradation products and so on.

Individual X-ray photons produced at the specimen

surface create an ionisation charge in a silicon diode, the charge being proportional to photon energy. The signal is amplified, measured and stored in a ferrite core memory. A display of the spectrum of photon counts against photon energy is then produced. This allows rapid element analysis (atomic number  $> 8$ ).

The results from the S.E.M. and chemical analysis will be described in Chapters 4 and 5. For more details about these and other surface techniques the reader is referred to review papers by Buckley (56) and Ferrante (58), and the book by Phillips (57).

#### 3.3.4 Ferrography

The ferrograph used in this thesis is the Duplex Ferrograph analyser. Figure 3.4 shows a simplified schematic of the ferrograph in its analyser mode. The Duplex has a direct reading capability in which the optical densities of the deposits at selected points may be determined, however this technique is mainly applicable to a continuous monitoring system and was not employed.

The test lubricant is diluted with a solvent to enhance the precipitation of wear particles and pumped across a transparent substrate, mounted at an incline. The slide is situated in a high gradient magnetic field and debris is attracted to the substrate along the flux lines of the magnet. The slide is flushed with solvent to remove residual oil and fix the particles to the substrate.

The slide may then be examined under an optical

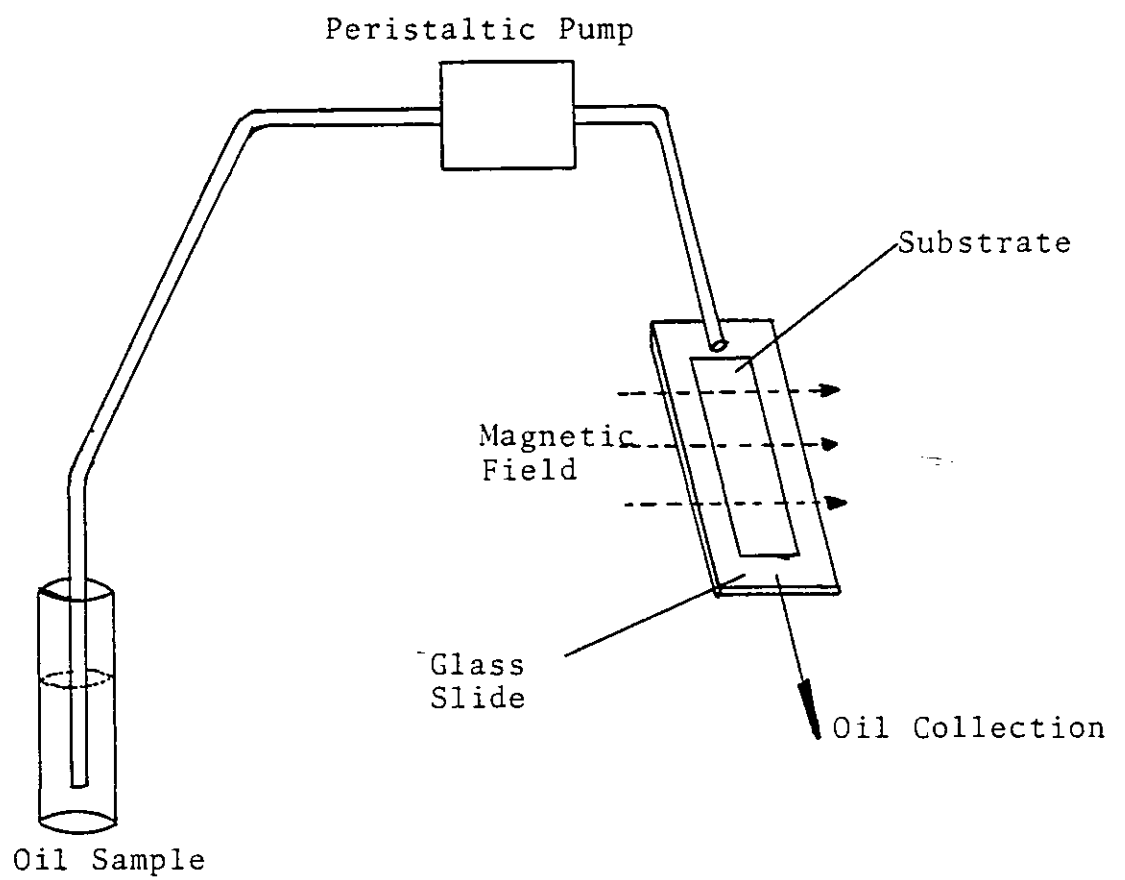


FIG 3.4 Simplified Schematic Diagram of Ferrograph



microscope for evidence of specific types of debris (e.g. delamination particles). A bichromatic microscope is often used with reflected red light and transmitted green light. Metallic particles reflect red light and block the green light (appear red) whilst particles composed of compounds allow much of the green light to pass and appear green. Before analysis under the S.E.M. the slide must be coated with an electro-conductive layer (e.g. gold or carbon).

For more details on this topic the reader is referred to Bowen et al (59), Reda et al (60) and Scott et al (61).

#### 3.3.5 Micro-sections

In order to investigate the structure of the liner surface and subsurface for different conditions a series of micro-sections were carried out. The main aims of this technique were:

- 1) To compare liner surface and subsurface deformation obtained for the different lubricants.
- 2) To investigate the occurrence of glaze formation and to gain any further information on the possible mechanisms of bore polishing.

#### 3.3.6 Other techniques

##### a) Talysurf

The talysurf was used in order to compare surface

roughness of non-polished and polished surfaces obtained in the tests. This is discussed in more detail in section 3.5.

#### b) Zinc analysis

In order to estimate the concentration of zinc in the commercial oils described on page (80) a zinc analysis was conducted. Each lubricant was treated with a diluted mixture of acids (nitric, sulphuric, perchloric) and gently heated until all that was left was the metallic composition of each oil (e.g. calcium, magnesium and zinc). This was then diluted and Atomic Absorption used to determine the concentration of zinc in each oil. The zinc concentration is indicative of the ZDDP concentration of each oil. This is discussed in more detail in Chapter 4.

### 3.4 TEST PROCEDURE

The electronic apparatus, described in Chapter 2, was switched on 30 minutes before the start of each test to allow it to 'warm-up'. The cleaning procedure described on page (81) was then conducted and the apparatus carefully assembled. The test oil was added to the oil bath either by a syringe cleaned in toluene and acetone or directly from the sample bottle. Care was taken to clean the thermocouple with acetone before the start of each test. The final temperature, temperature rise rate, frequency and logarithmic potentiometer were then set at the values described in Section 3.1. The test was then started, with the oil at a room temperature of  $\sim 20^{\circ}\text{C}$ . At the end of the

test the entire apparatus was switched off, the load removed and the oil bath allowed to cool for at least 1½ hours. The specimens were then removed and cleaned as described previously.

### 3.5 PRELIMINARY RESULTS

The preliminary results had two specific aims:

- 1) To determine the repeatability of the test results, in terms of pen recorder data and visual appearance of the liner specimens.
- 2) To determine whether a phenomenon resembling bore polishing could be obtained in the H.F.R. apparatus, in particular to determine whether the H.F.R. apparatus could distinguish between two reference oils. (One of low bore polishing percentage and one of high bore polishing percentage as defined by the Ford Tornado test).

#### 3.5.1 Repeatability

The H.F.R. apparatus was run for a series of nine tests using a base stock used by Mills (28) and designated B2. The test programme is detailed below:

| LUBRICANT | TEST TEMPERATURE | TEST TIME | NUMBER OF TESTS |
|-----------|------------------|-----------|-----------------|
| B2        | 200°C            | 2 hrs     | 3               |
| B2        | 250°C            | 2 hrs     | 3               |
| B2        | 300°C            | 1 hr      | 3               |

TABLE 3.2 REPEATABILITY TEST PROGRAMME

The results of these tests can be seen on Pages (96-98) The friction coefficient and contact voltage data has been scaled down and plotted by hand. Since the analysis of the pen recorder data is based upon general trends in the two chart recorder outputs, small variations in friction coefficient and contact voltage are ignored.

The photographs on Page (99) are of the liner surface as seen by the S.E.M. and are typical of the photographs obtained using this technique. To minimise the amount of experimental data, especially photographs, in this and other chapters only a selection of the most representative photographs have been included.

### Conclusions

The two photographs both indicate that the liner surfaces, although apparently rough, are devoid of honing lines. They are both polished and there is evidence of wear debris on each liner. Repeatability is clearly very good.

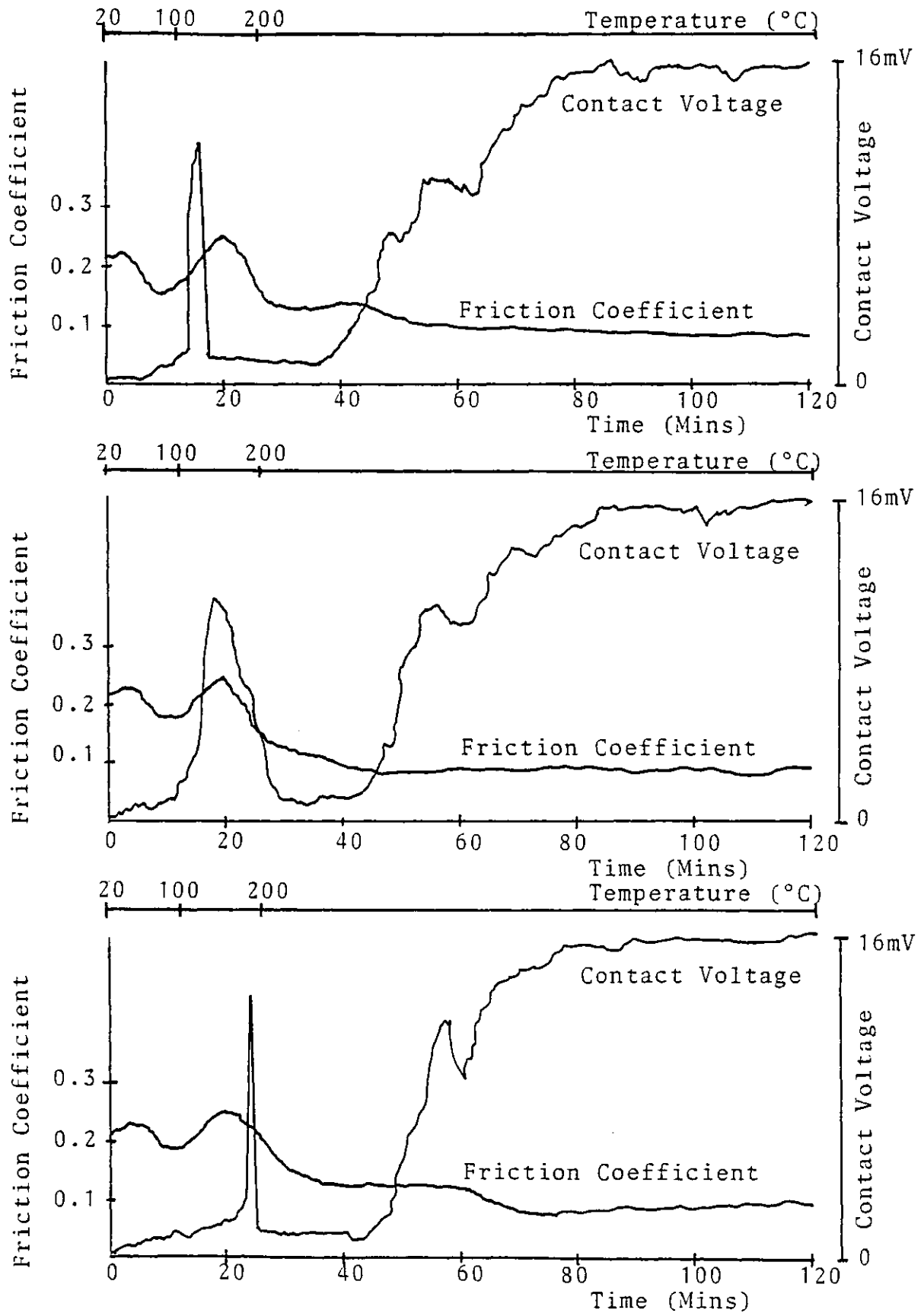


FIGURE 3.5 Repeatability Tests. B2 at 200°C

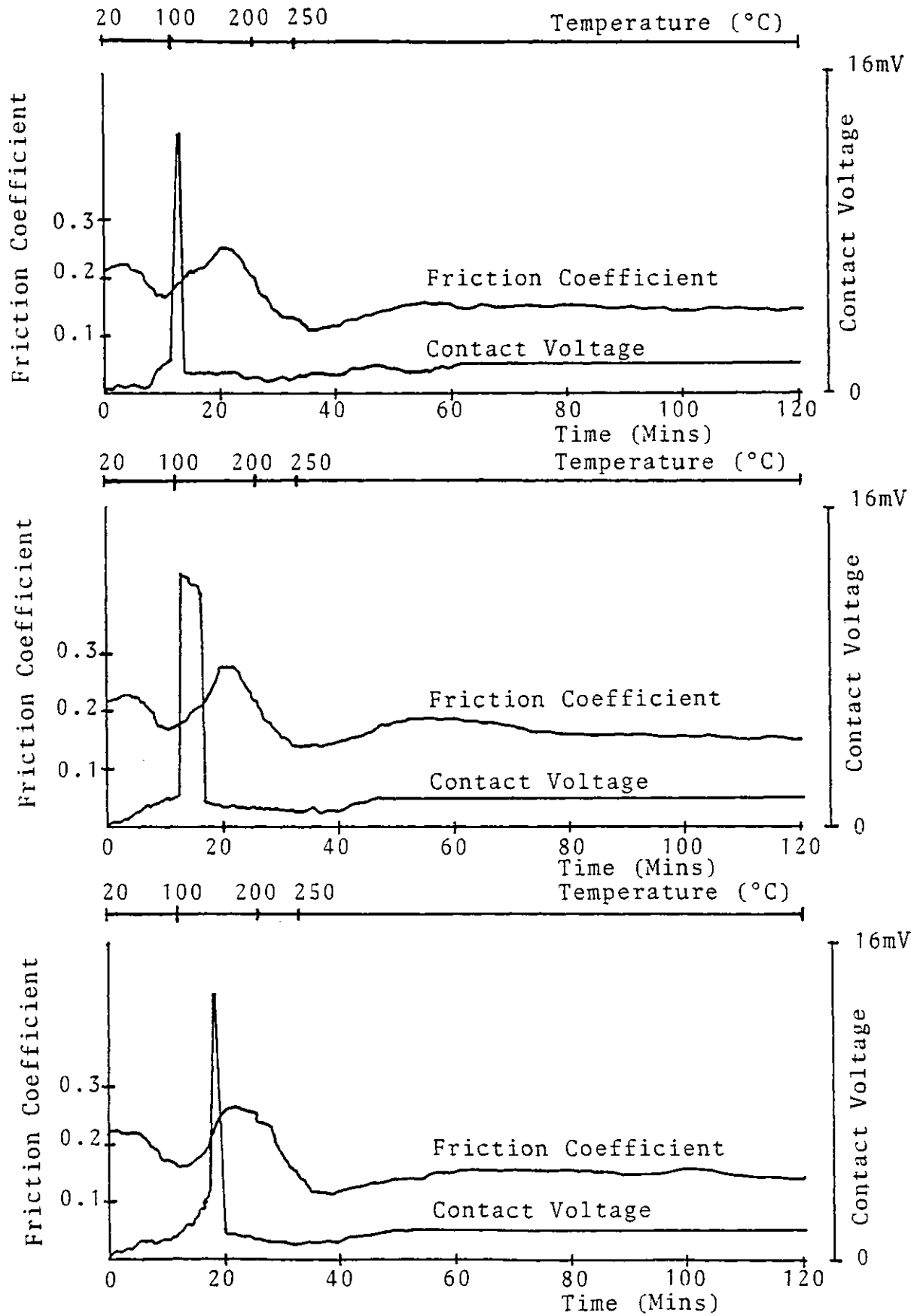


FIGURE 3.6 Repeatability Tests. B2 at 250°C

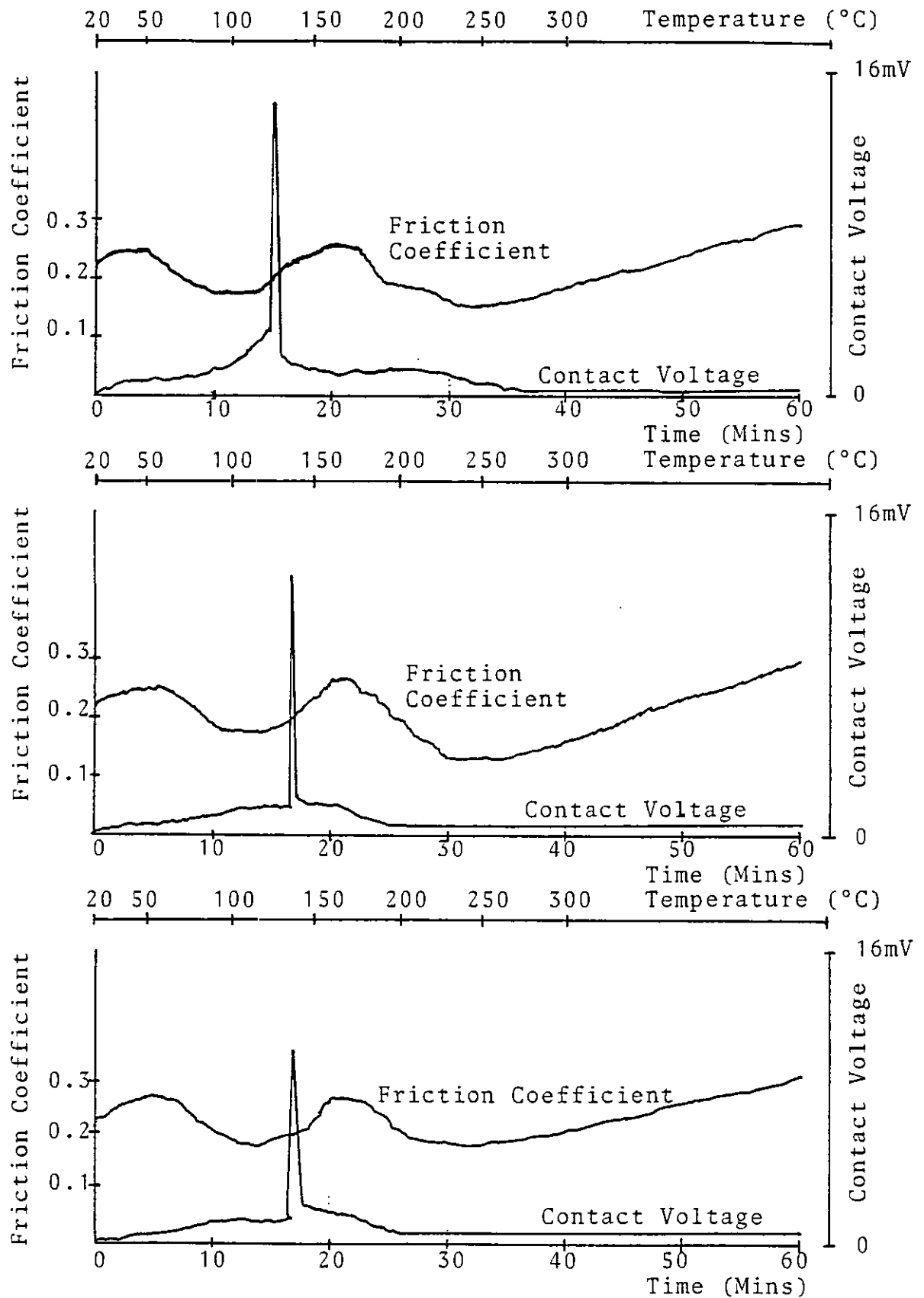


FIGURE 3.7 Repeatability Tests. B2 at 300°C



Figure 3.8 S.E.M. View of Liner with B2 at 250°C (500x)

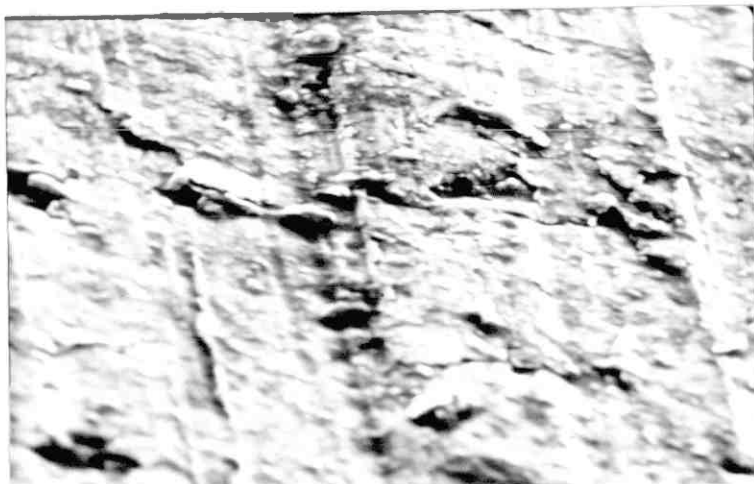


Figure 3.9 S.E.M. View of Liner with B2 at 250°C ( 500x)



### 3.5.2 Bore Polishing?

It was necessary at the outset to determine whether bore polishing, as defined by Wilson and Calow (33) and others, could be obtained using the H.F.R. apparatus. For this purpose the reference oil C2 (45% bore polishing percentage) was tested for a range of temperature and time conditions. Figures ( 3.10-3.12 ) show clearly the similarity between the Ford Tornado liner, the liner taken from a service engine with bore polishing and the liner used in the H.F.R. apparatus. Figures 3.13 and 3.14 are included for reference.

### 3.5.3 Comparison of bore polishing in two oils

Having established that bore polishing could be produced with the H.F.R. apparatus the next stage was to determine whether two oils of known bore polishing percentage could be segregated by the H.F.R. apparatus. For this purpose the two oils C1 (17% bore polishing percentage - b.p.p.) and C2(45% b.p.p.) were tested as detailed in Table 3.3

| OIL | TEST TEMPERATURE    | TEST DURATION                |
|-----|---------------------|------------------------------|
| C1  | 200°C, 250°C, 300°C | 2hrs, 2hrs, 1hr respectively |
| C2  | 200°C, 250°C, 300°C | 2hrs, 2hrs, 1hr respectively |

TABLE 3.3 INITIAL BORE POLISHING TESTS

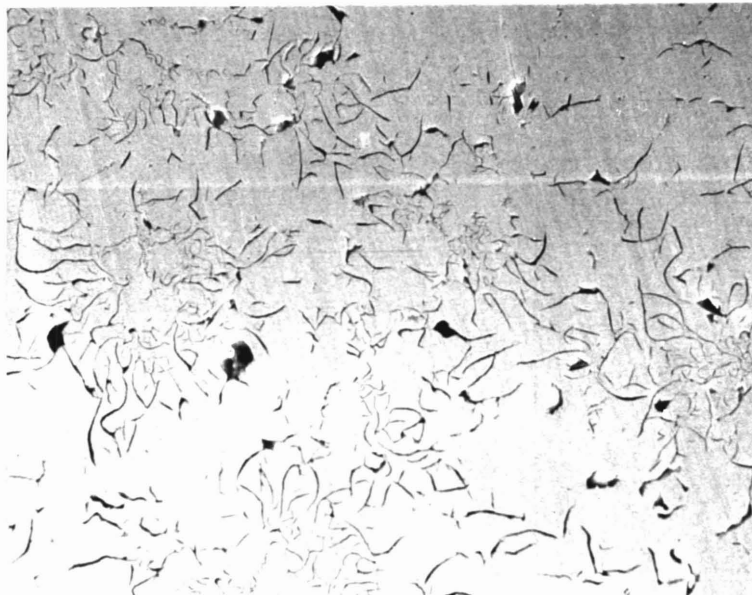


Figure 3.10 S.E.M. View of Ford Tornado Test Liner with Polishing (200x)



Figure 3.11 S.E.M. View of Service Engine Liner with Polishing (200x)



Figure 3.12 S.E.M. View of H.F.R. Test Liner with Polishing (200x)



Figure 3.13 S.E.M. View of Untested H.F.R. Liner (200x).

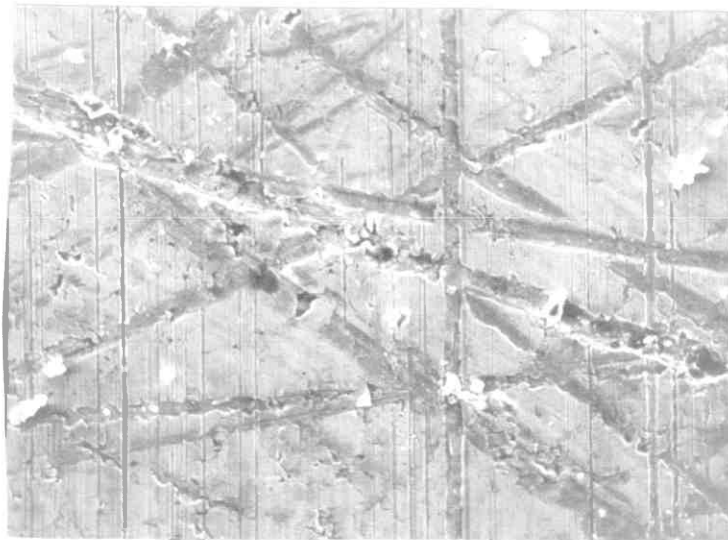


Figure 3.14 S.E.M. View of non- Polished Ford Tornado Liner  
(200x).

The photographs on Page 104 are representative of the six tests conducted in which the liner surface of C1 is much rougher than that of C2 as evidenced by the removal of the original honing pattern in C2. These tests show clearly that the H.F.R. apparatus can distinguish between two oils of known bore polishing percentage. Photograph 3.15 shows honing lines visibly whilst photograph 3.16 shows polishing.

In order to make further comparison between these two liners a talysurf profile was obtained for each liner as shown on page 105. There are two observations to be made from this study, namely:-

- 1) The centre line average (C.L.A.) values for each liner indicate that the polished specimen has a surface profile similar to that defined by Wilson and Calow (33) and others.
- 2) In the case of the polished specimen there is evidence of removal of liner material to a greater extent than the non-polished liner. i.e. this study suggests that polishing is not a 'filling-in' of honing lines.

#### 3.5.4 Oxidation

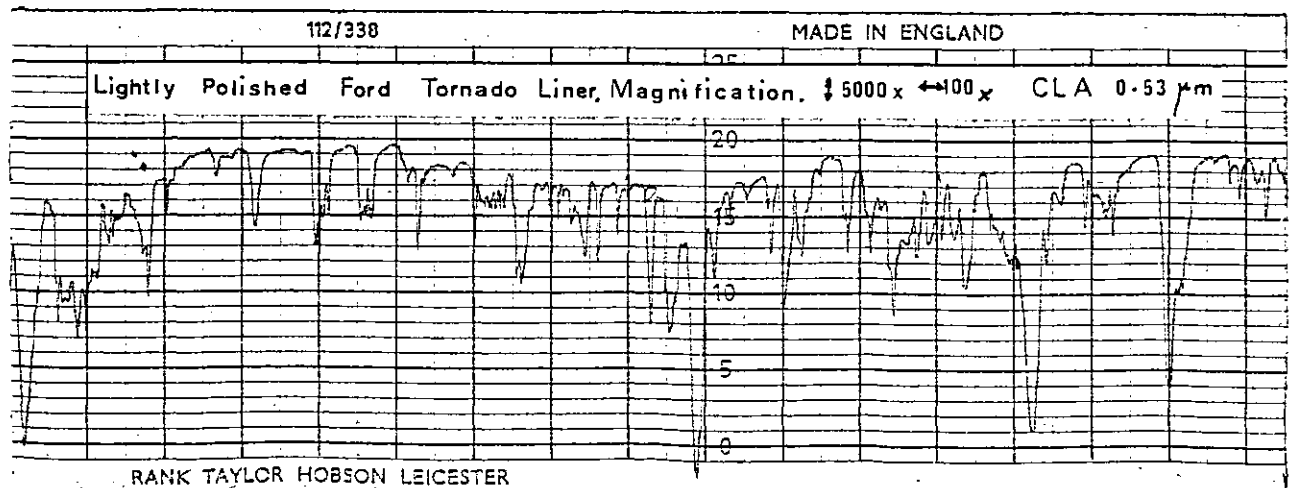
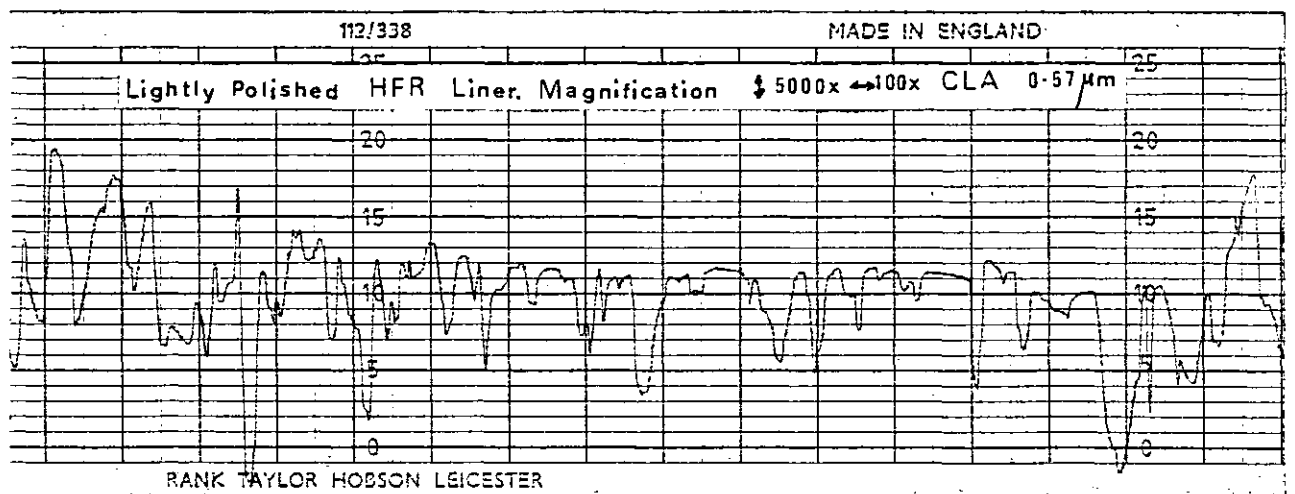
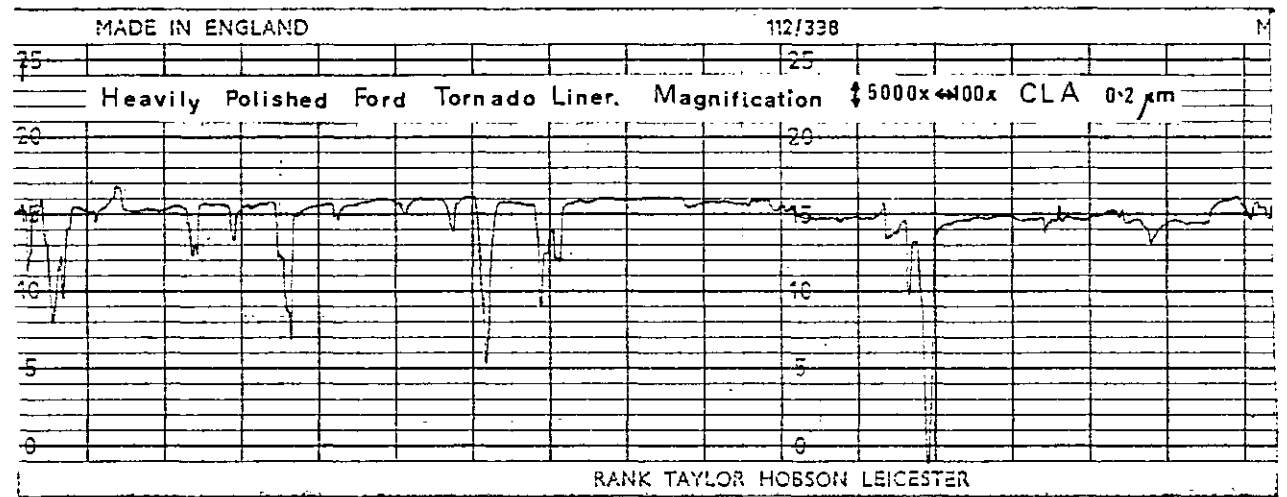
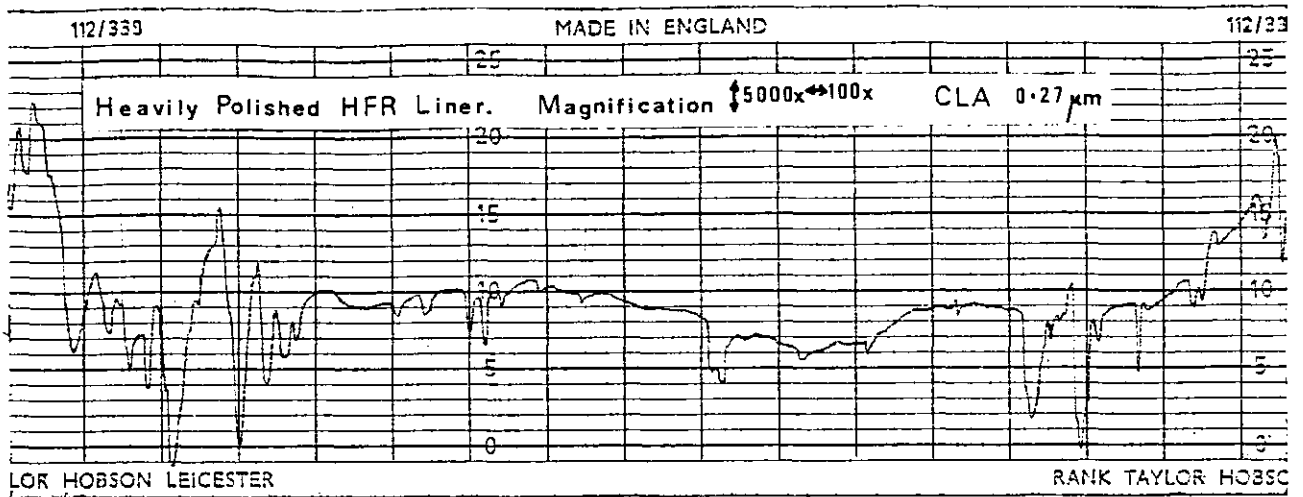
As mentioned on Page (74) it was discovered that at high temperatures (300°C), and test times in



Figure 3.15 S.E.M. View of Liner with C1 at 200°C (500x)



Figure 3.16 S.E.M. View of Liner with C2 at 200°C (500x)



excess of 1 hour the oil boiled off from the contact leaving it exposed. The effect on the contact voltage was very dramatic as can be seen on Page 107 in which a mineral base stock is heated up to 300°C and held constant, the total test time being 2 hours. For the first 80 minutes a normal trace is seen for both friction coefficient and contact voltage. However after 80 minutes the oil in the contact was boiled off leaving only a small pool of oil, which rapidly became oxidised. This was indicated by the rise in contact voltage up to a maximum of 16mV. This led to a corresponding drop in friction coefficient.

Clearly this was undesirable since it was necessary to maintain the same test conditions for each lubricant, and the formation of a highly oxidised pool of lubricant only occurred at high temperatures. To avoid repetition of this occurrence, high temperature tests were conducted for 1 hour.

### 3.6 Conclusions

The preliminary testing highlighted several important points.

- 1) The H.F.R. apparatus was capable of producing very repeatable results, both in terms of pen recorder data and scanning electron microscope photographs.

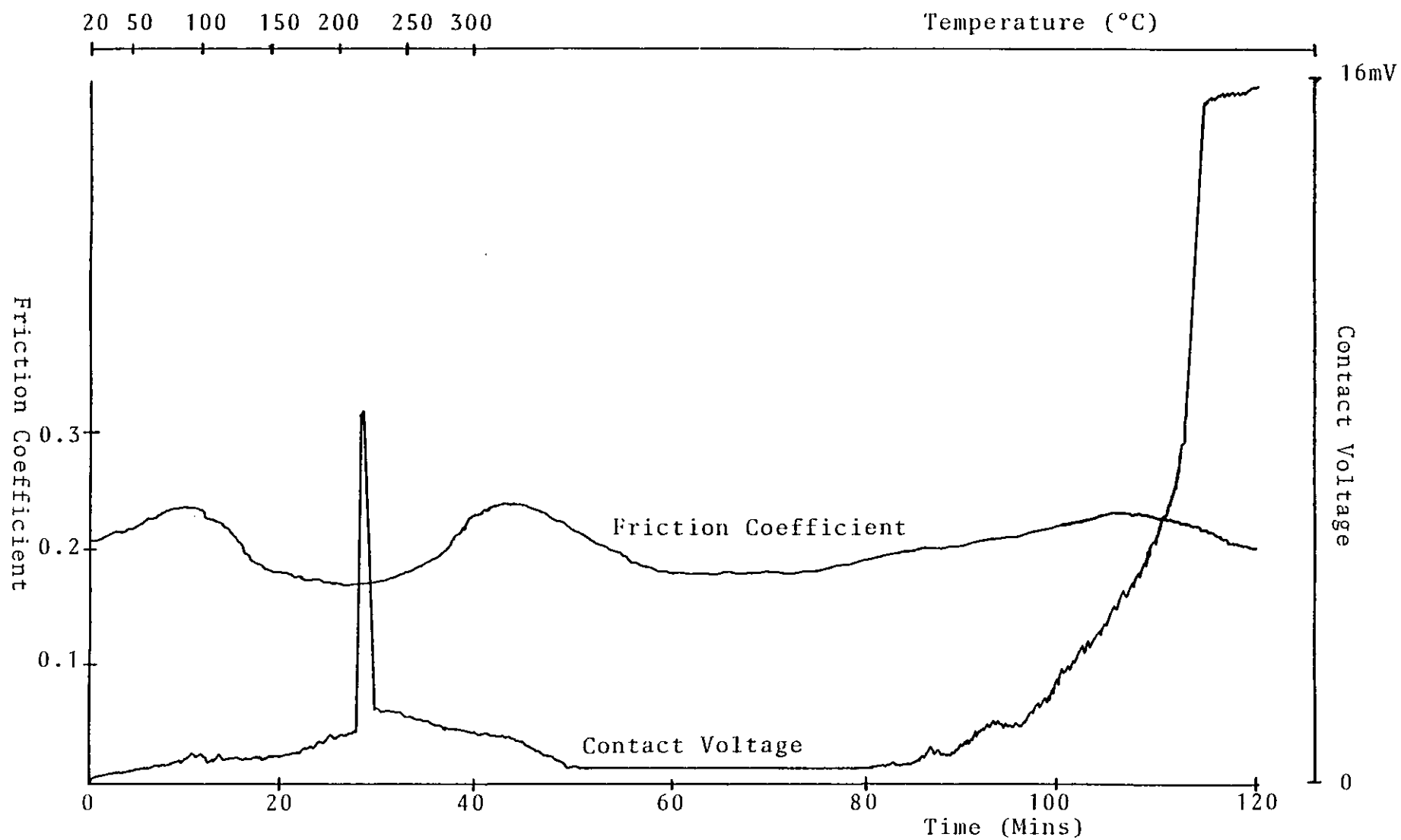


FIGURE 3.18 B2 at 300°C for 2 hours



2) A phenomenon closely resembling bore polishing in the Ford Tornado test and a service engine was observed.

3) The H.F.R. apparatus was capable of separating two commercial reference oils in terms of severity of bore polishing and this correlated well with information provided on each oil.

4) Owing to the likelihood of oxidation of the lubricant at high temperatures, tests conducted at 300°C should be conducted for 1 hour rather than 2 hours.

C H A P T E R 4

Bore polishing tests with 6 commercial oils

## CHAPTER 4

### Bore Polishing Tests with 6 Commercial Oils

#### 4.1 Introduction

The preliminary tests described in Chapter 3 highlighted the ability of the H.F.R. apparatus to achieve an effect similar to bore polishing and also to differentiate between two reference oils. This chapter describes experiments conducted on the complete set of 6 commercial oils described on Page (80). The experiments had the following aims.

- 1) To attempt to correlate visually the polishing seen on H.F.R. liners with Ford Tornado data.
- 2) To prepare a number of micro-sections in order to observe the microstructural changes associated with heavy polishing.
- 3) To conduct a microprobe analysis (m.p.a.) of H.F.R. liner surfaces to determine the chemistry of worn surfaces.
- 4) To carry out ferrography on a number of run H.F.R. lubricants for evidence of wear debris in the oil.
- 5) By inclining the H.F.R. apparatus and drip feeding the lubricant it was hoped to simulate practical conditions more accurately. The analyses described above were then to be conducted, and compared with immersed contact experiments.

6) To conduct a zinc analysis of the commercial oils in order to gain knowledge of their ZDDP concentration.

7) To use the information gained by the various techniques in order to

a) Attempt to characterise the nature of a bore polished surface

b) Gain further understanding of the mechanisms of bore polishing.

#### 4.2 Test Programme

The tests described in this chapter may be split into two sections. These are listed below.

##### 4.2.1 Immersed Contact Tests

These tests were conducted in the manner described in Chapter 3 ( P 93).At the end of each test the liner specimens were cleaned in readiness for the S.E.M. analysis and are summarised in Table 4.1 below:-

| OIL | TEST TEMPERATURES (TEST TIMES)       |
|-----|--------------------------------------|
| C1  | 200°C(2hrs), 250°C(2hrs), 300°C(1hr) |
| C2  | 200°C(2hrs), 250°C(2hrs), 300°C(1hr) |
| C3  | 200°C(2hrs), 250°C(2hrs), 300°C(1hr) |
| C4  | 200°C(2hrs), 250°C(2hrs), 300°C(1hr) |
| C5  | 200°C(2hrs), 250°C(2hrs), 300°C(1hr) |
| C6  | 200°C(2hrs), 250°C(2hrs), 300°C(1hr) |

TABLE 4.1 Immersed contact tests on commercial oils

#### 4.2.2 Drip feed tests

The drip feed tests were conducted with the same operating parameters described in section 3.1. The only difference with this set of tests is that the oil bath was replaced with a similar oil bath with a downspout, described on Page (53), and the oil was continuously fed to the contact.

At the outset, a number of short experiments were conducted to examine the effect of drip feed rate upon friction force and contact voltage results and also liner surface results. It was observed that whilst the pen recorder data was sensitive to changes in the oil feed rate it was not very sensitive to steady values of feed rate, i.e. the pen recorder data would respond to a change in feed rate but would then return to its previous readings. This remained true until the feed rate fell below one drop per 1½ minutes. At this point the oil was seen to become highly oxidised since a thick film was established in the manner illustrated on Page 107. The oil was fed to the liner surface from a 50 c.c. burette over a range of feed rates and it was found that a feed rate of 1 drop every 20 seconds was very easy to control and produced no detectable change from a rate of 1 drip every 2 seconds. There was no detectable change in surface appearance of the liner specimens for each rate tested. Consequently, a rate of 1 drop every 20 seconds was chosen as the standard

feed rate and this corresponds to a flow rate of 5 c.c./hour.

The sketch on Page 114 shows the position of the burette with relation to the piston ring and the cylinder liner. The reasons for the position of the burette are briefly discussed below.

a) Oil drop temperature

The temperature of the oil just after it had passed through the contact was measured for a range of burette positions along the liner with the thermocouple. It was found that, with a feed rate of 5 c.c./hour and temperatures in the range  $150^{\circ}\text{C}$  to  $300^{\circ}\text{C}$ , a minimum distance of 10 mm between the piston ring and initial oil contact position was needed for the oil to attain the contact temperature. The burette was placed 15 mm from the piston ring as shown on Page 114.

b) Constant feed rate

It was found that if the burette was placed within 50 mm of the hot liner surface the oil feed rate was not constant. This occurred because the oil at the base of the burette became heated and its viscosity was not constant. To eliminate this problem the burette was placed

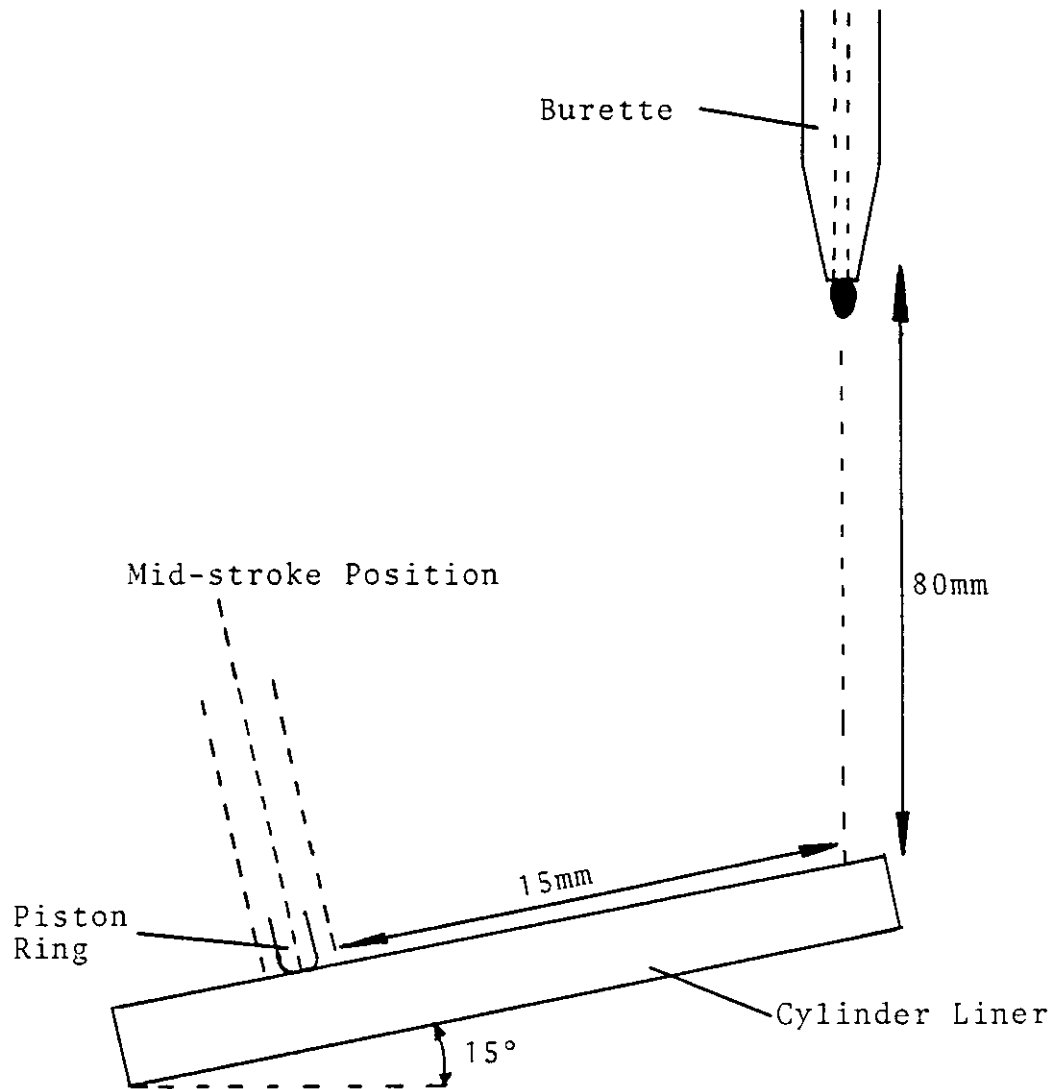


FIGURE 4.1 Drip Feed System (not to scale)

80 mm above the liner surface. This is shown on Page 114

At the conclusion of each test the liner specimens were cleaned in readiness for the S.E.M. analysis. The burette was also cleaned in toluene and acetone prior to each test as well as those items listed on Page (81). The tests conducted in this section are summarised in Table 4.2 below.

| OIL | TEST TEMPERATURE (TEST TIME)            |
|-----|---|
| C1  | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |
| C2  | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |
| C3  | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |
| C4  | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |
| C5  | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |
| C6  | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |

TABLE 4.2 Drip feed tests on commercial oils

### 4.3 Results

#### 4.3.1 Immersed contact tests

The sketches on Pages 116-121 show pen recorder results for the tests summarised in Table 4.1.



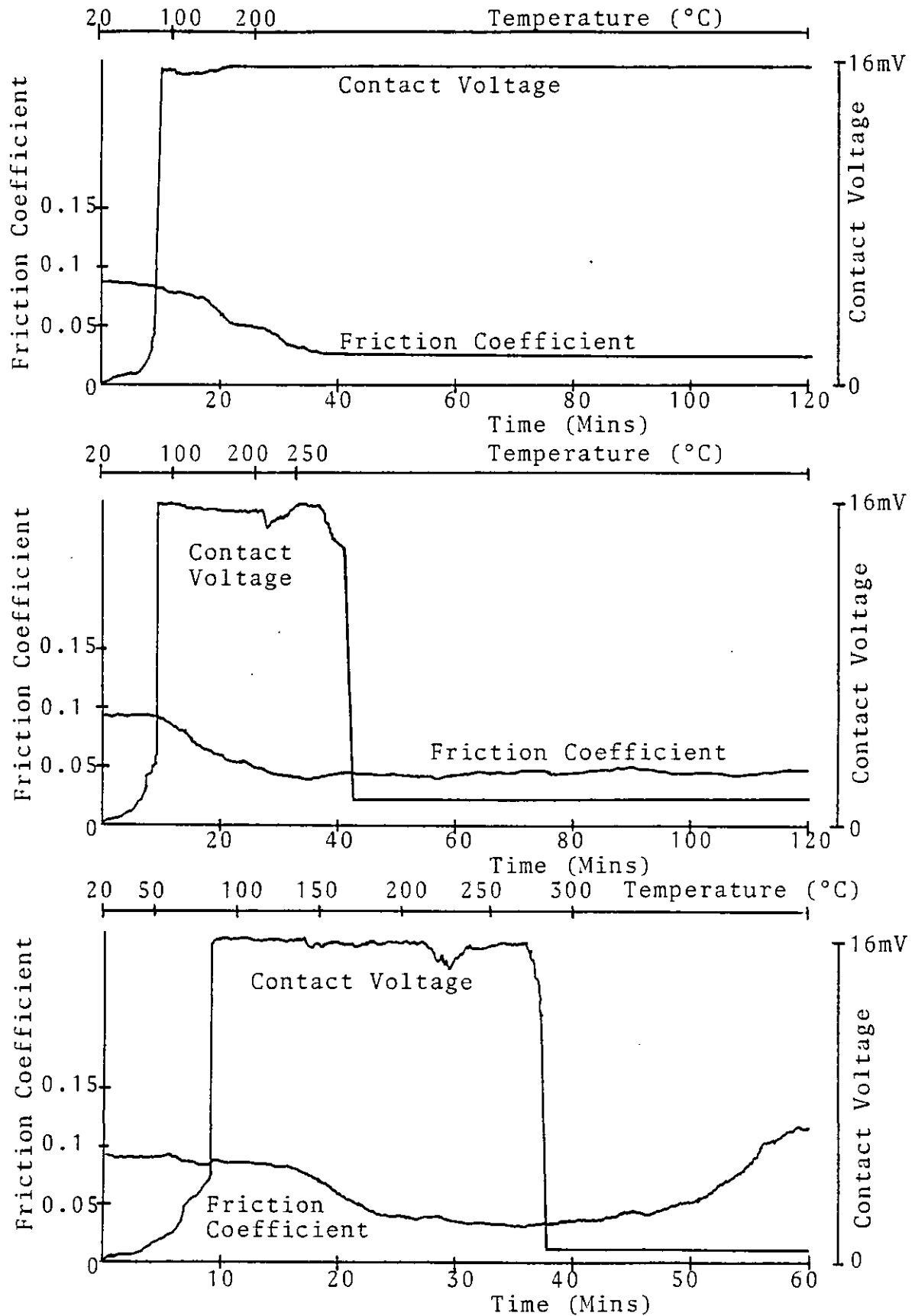


FIGURE 4.2 C1 at 200°C, 250°C, 300°C (immersed)

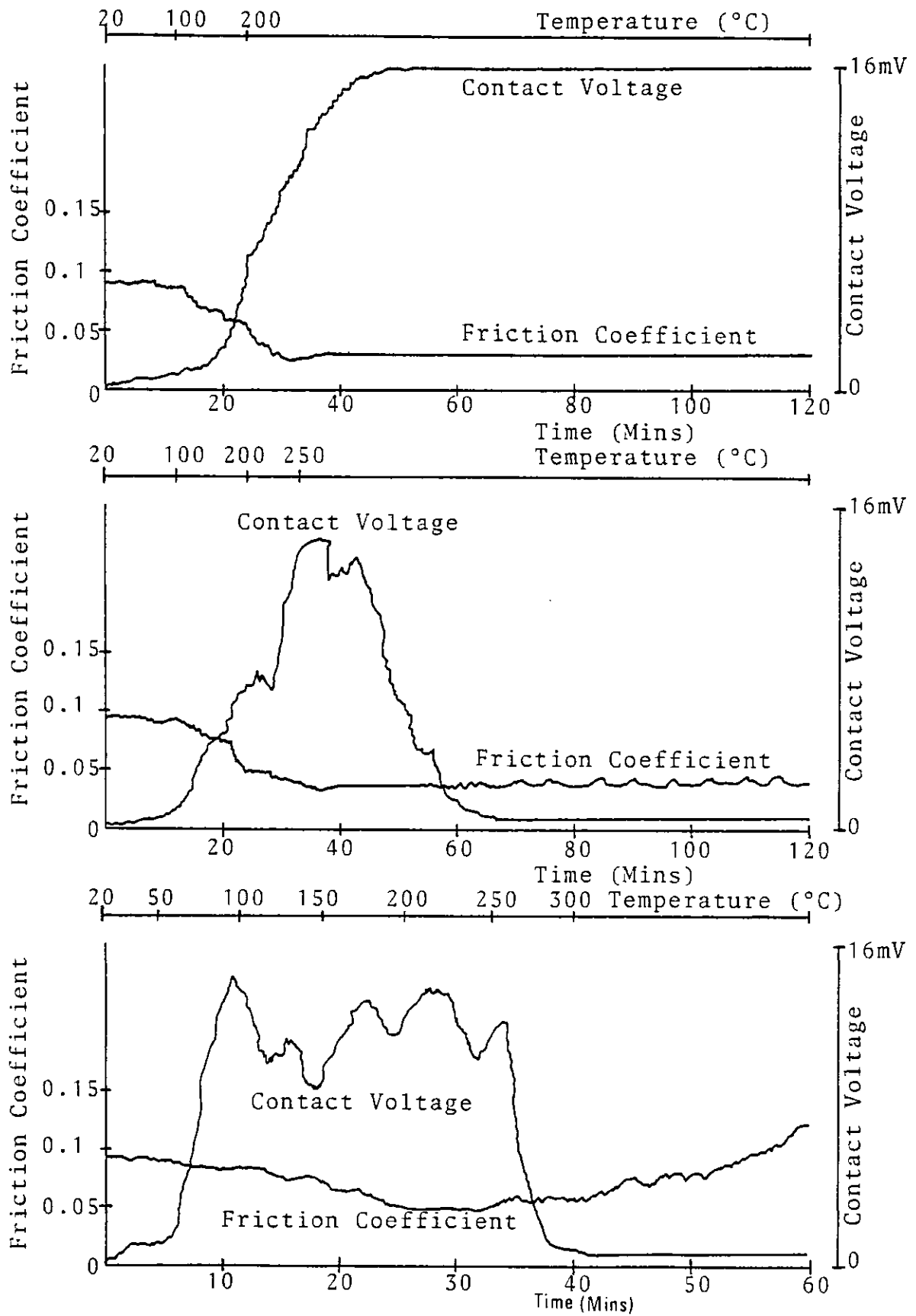


FIGURE 4.3 C2 at 200°C, 250°C, 300°C (immersed)

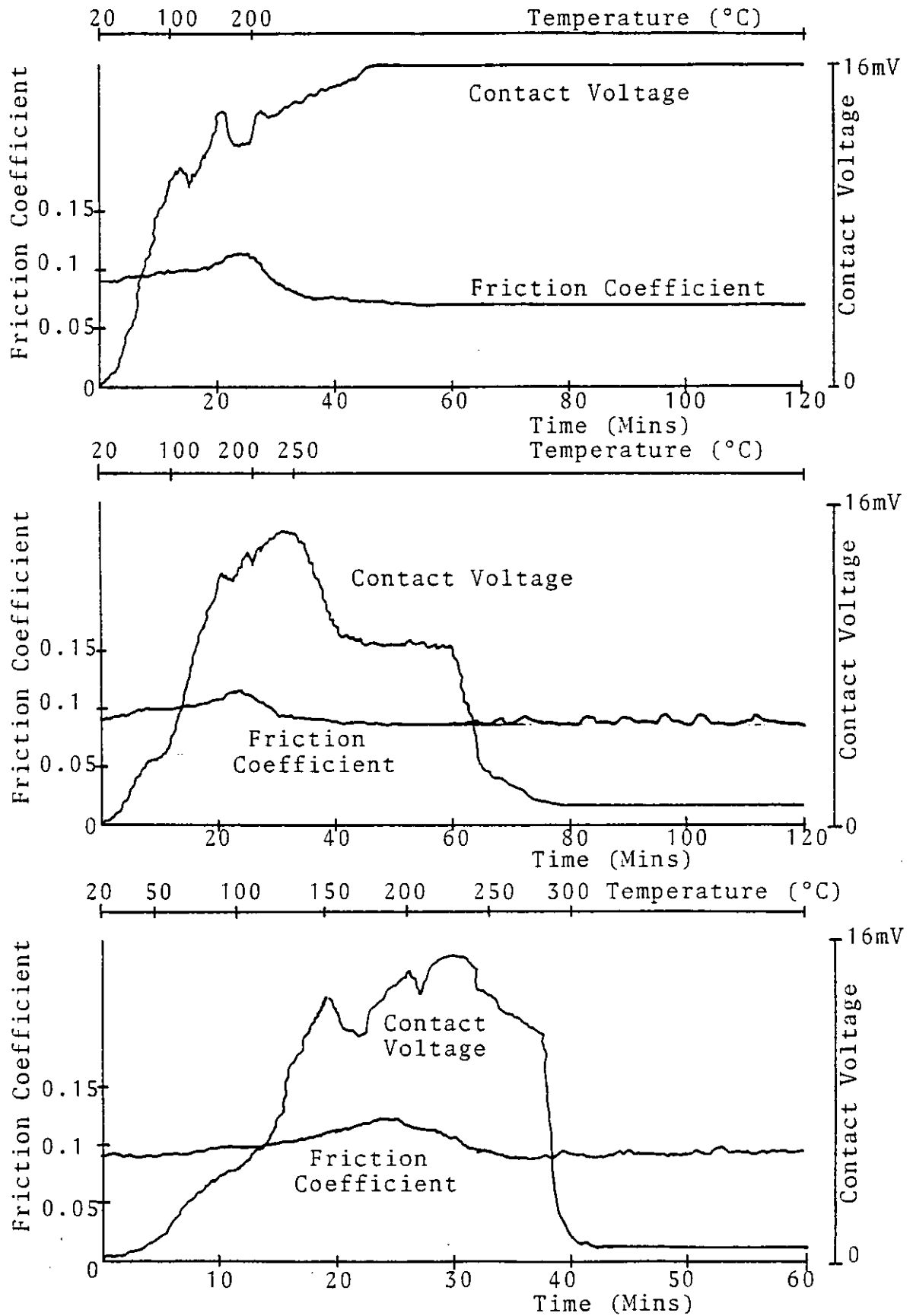


FIGURE 4.4 C3 at 200°C, 250°C, 300°C (immersed)

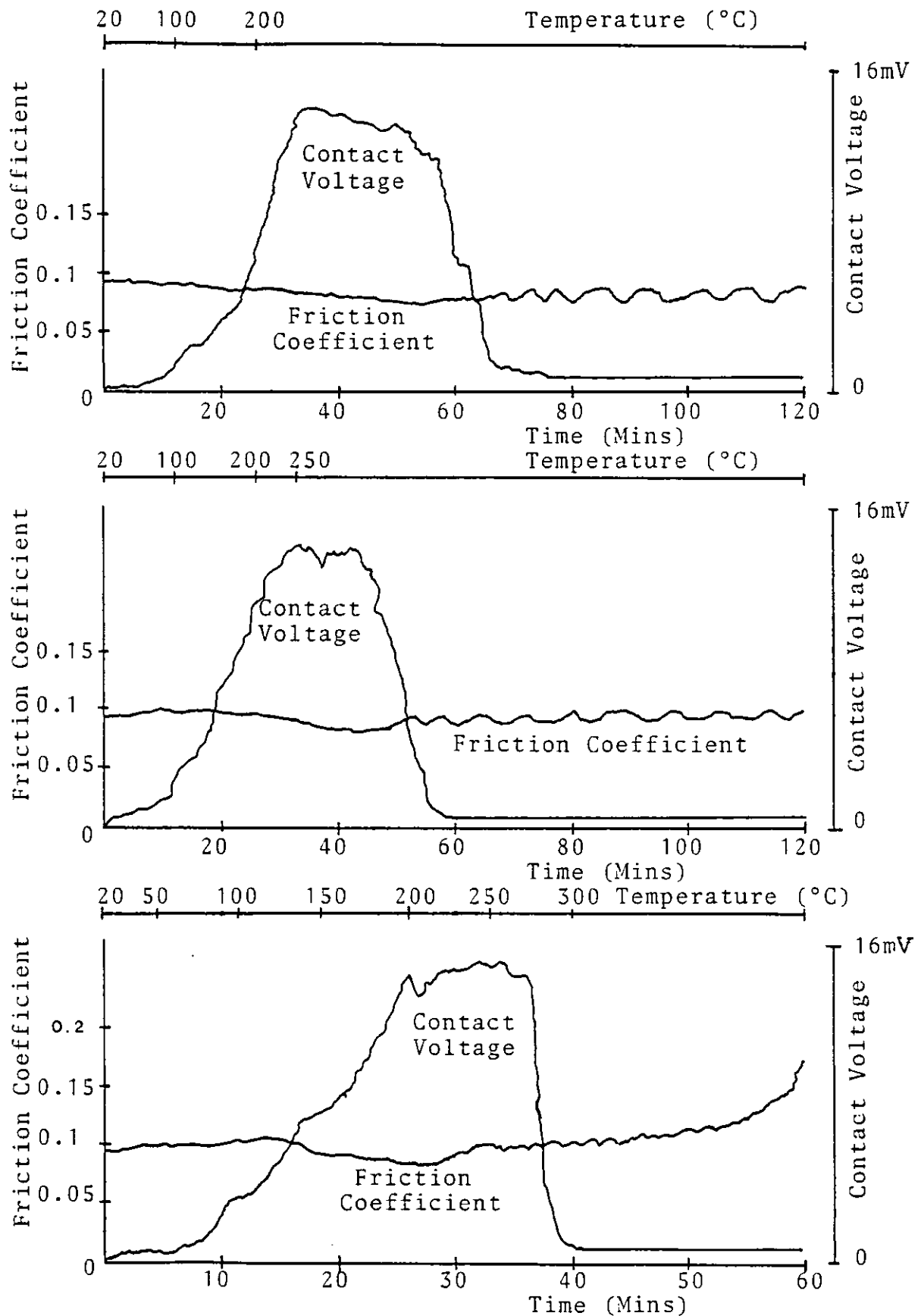


FIGURE 4.5 C4 at 200°C, 250°C, 300°C (immersed)

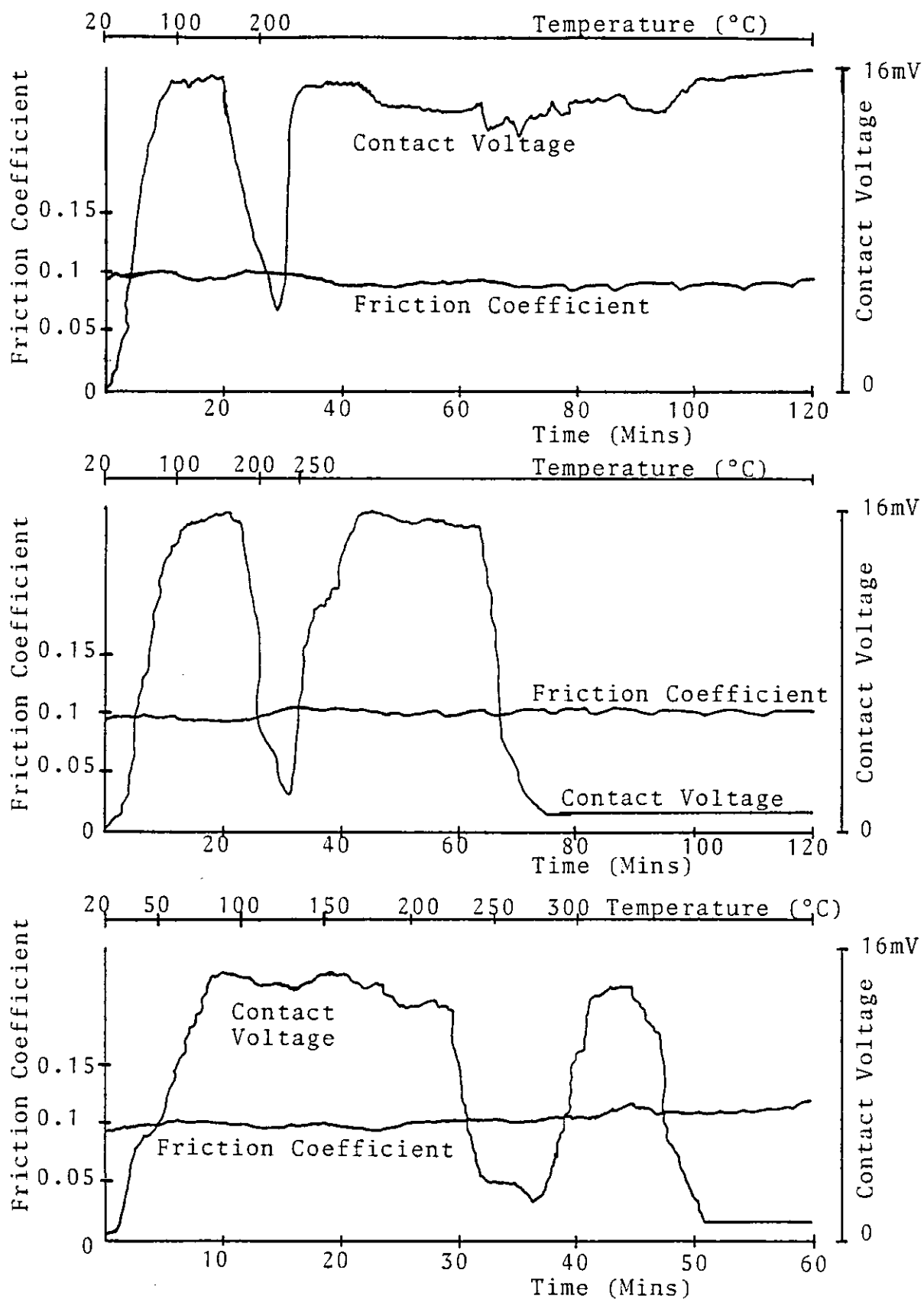


FIGURE 4.6 C5 at 200°C, 250°C, 300°C (immersed)

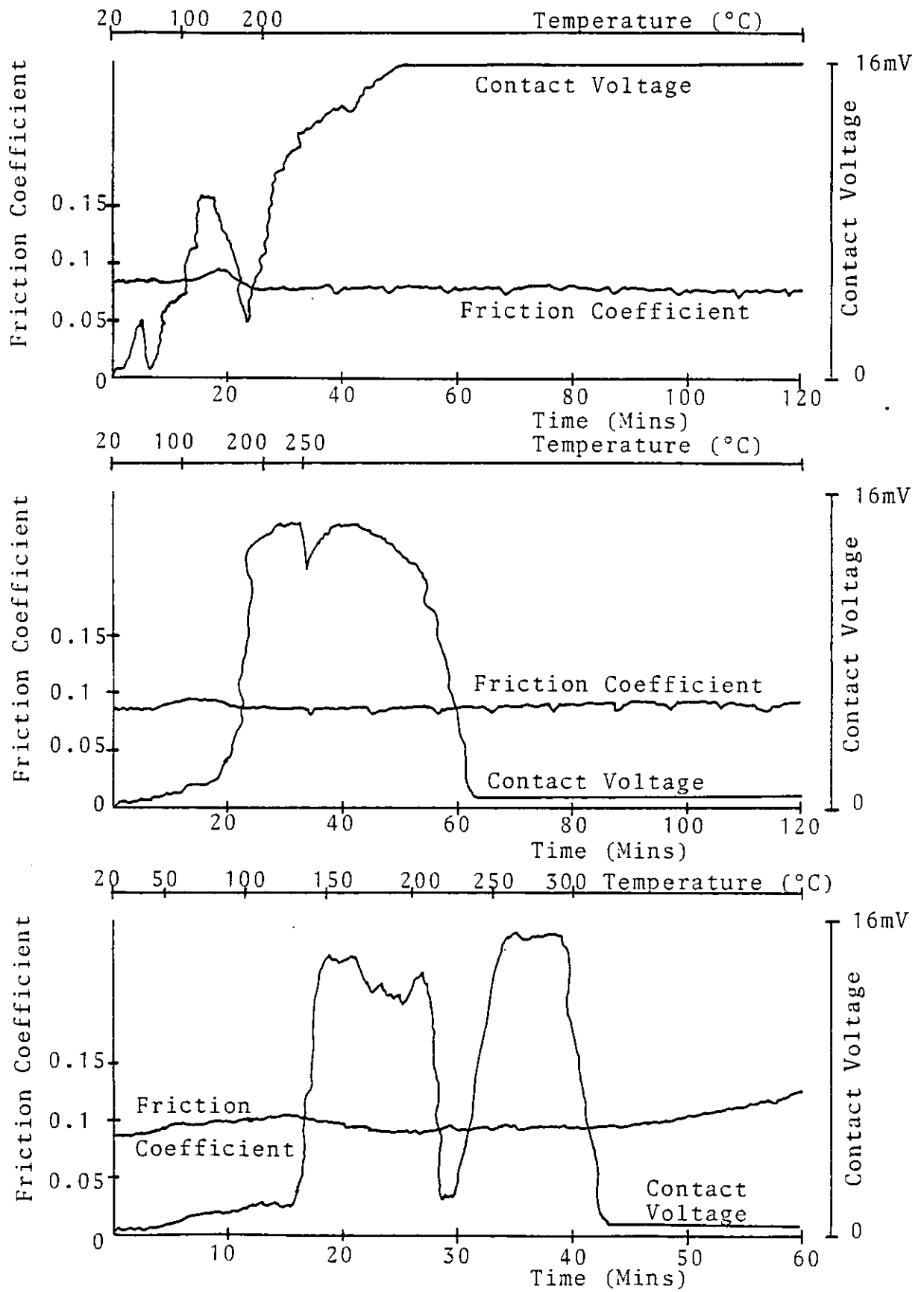


FIGURE 4.7 C6 at 200°C, 250°C, 300°C (immersed)

The photographs on Pages (125-127) are representative of the surface examination conducted by S.E.M.

#### 4.3.1.1 Pen recorder data

For each of the 200°C tests (upper graph) the contact voltage indicated a thick boundary film with the exception of C4. Oils C1 and C2 had almost identical friction coefficient traces, both falling to 0.04, whilst the other oils were of the order of 0.1. C1 and C2 indicated a very stable friction coefficient trace. Oil C4 exhibited a 'saw tooth' friction coefficient profile for half of the test which has a wavelength too large for stick-slip and was thought to be characteristic of a cyclic wear process. Oil C5 and C6 also showed signs of this process, however it was less well defined.

For the 250°C tests (centre graph) most of the oils, with the exception of C1, showed some degree of this 'saw tooth' profile on the friction coefficient plot. Oils C2 and C4 in particular showed this to be true. Between 40 and 65 minutes the contact voltage trace collapsed for most oils, with the exception of C5 which maintained a high contact voltage up to 80 minutes. The highest contact voltage was attained by C1.

For 300°C (lower graph) tests, all the oils showed a collapse of film thickness in the region

of 300°C. Oils C1, C2, C4 and C6 showed a sharp increase in friction coefficient after the collapse of the oil film. Oils C3 and C6 showed a slight increase in the friction coefficient, it is not clear from the pen recorder data why this occurs.

#### Deductions

- 1) For each oil tested it was noticed that at higher temperatures the oil film became unstable and usually collapsed. The friction coefficient also became less stable and had a tendency to increase at high temperature.
- 2) Oils C2 and C4 had a marked 'saw tooth' friction coefficient profile and had less stable oil films than the other oils. These oils were consequently considered to be likely to cause bore polishing.
- 3) It was not possible to rank the oils in terms of bore polishing severity from the pen recorder results, although indications of the likelihood of bore polishing could be gained.

#### 4.3.1.2 Visual S.E.M.

The photographs on pages 125-127 are representative of the visual examination conducted on the liner surfaces. From this study a number of points emerged.

- 1) There was an unexpectedly good correlation between engine tests and bench tests. Visually oils



C2 (Figure 4.8) and C4 (Figure 4.9) produced a smoother surface than the other oils, e.g. Figure 4.10. This is evidenced by the removal of the honing pattern. Engine tests also identified C2 (45%) and C4 (55%) as giving heavy bore polishing, although the test conditions are not identical. In particular there were no combustion products in the H.F.R. tests. It is clear from this observation that the lubricant has a more important role in the phenomenon of bore polishing than previously considered.

- 2) Higher temperatures appear to promote greater polishing. This is seen by a comparison of Figure 4.11 with Fig 4.12. There is some evidence to suggest possible corrosive pitting on the left hand side of Figure 4.11.
- 3) Evidence of plastic deformation was obtained, as seen in Figures 4.10, 4.12. This observation is particularly relevant when the honing pattern is visible, however in cases where the honing pattern is not clearly defined (as in Figure 4.8) it is not obvious whether deformation has occurred. This uncertainty will be investigated in the next section.
- 4) Evidence of delamination wear was found. This is illustrated in Figure 4.13, which is a high magnification view of a plate-like particle just leaving the surface. The existence of these wear particles is further described in Section 4.3.2.5.

It was noticed that these particles were only present

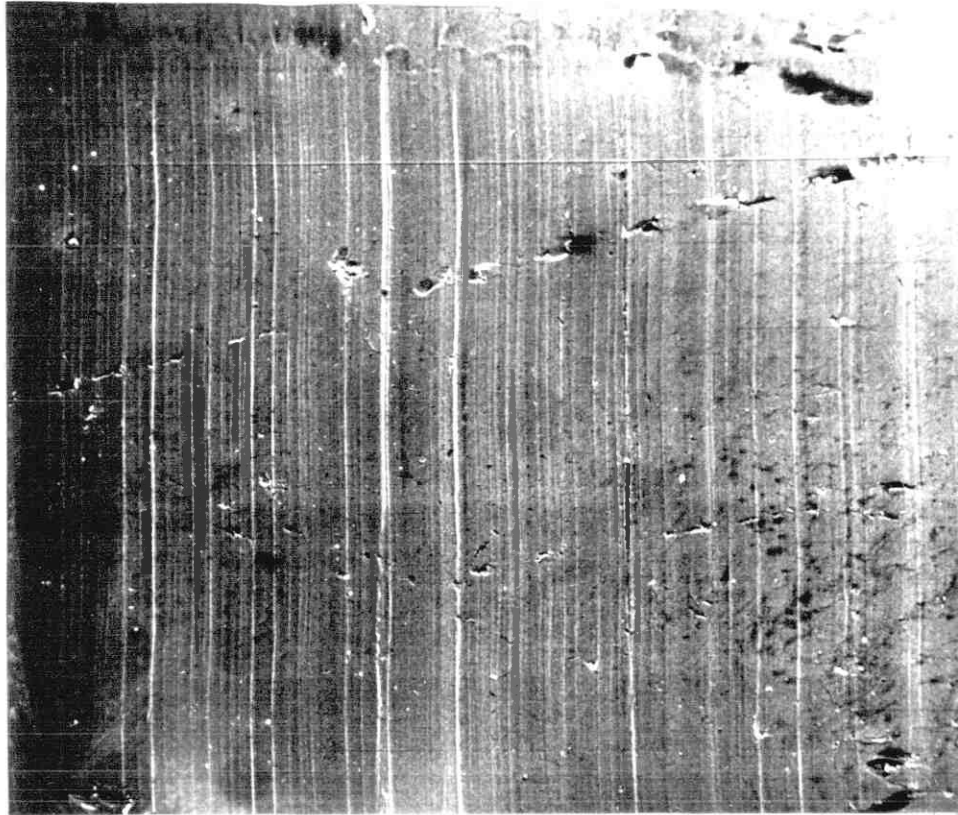


Figure 4.8 S.E.M. View of Liner with C2 at 250°C (immersed)  
(200x)



Figure 4.9 S.E.M. View of Liner with C4 at 250°C (immersed)  
(200x)

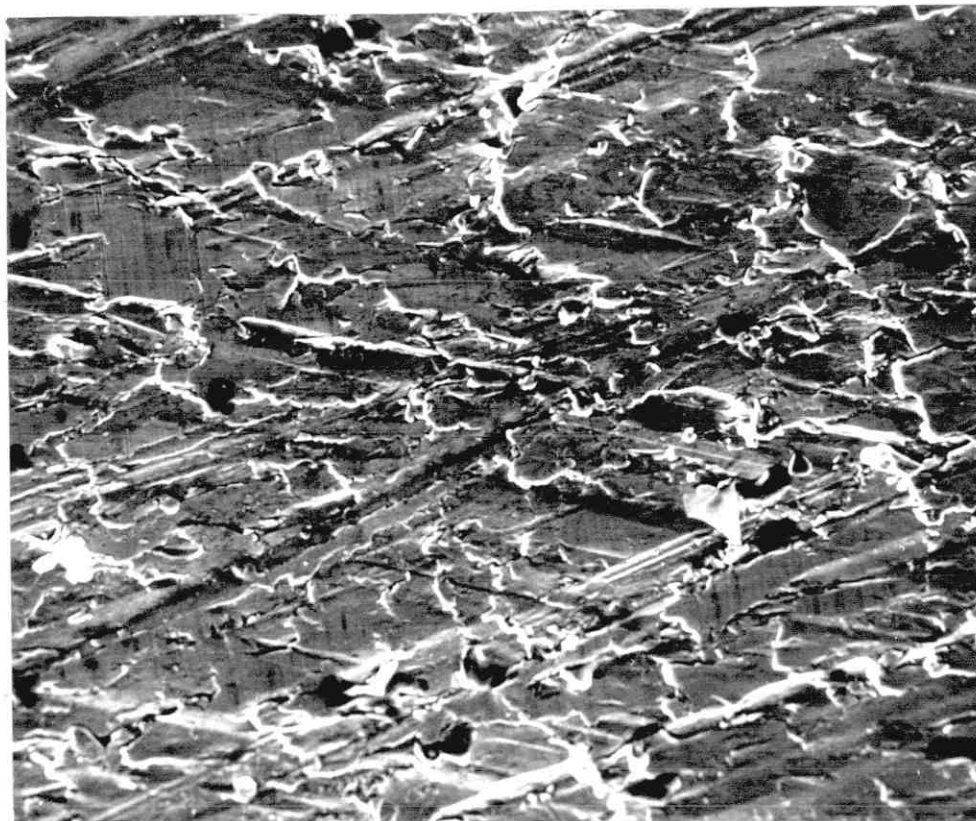


Figure 4.10 S.E.M. View of Liner with C1 at 250°C (immersed)  
(200x)

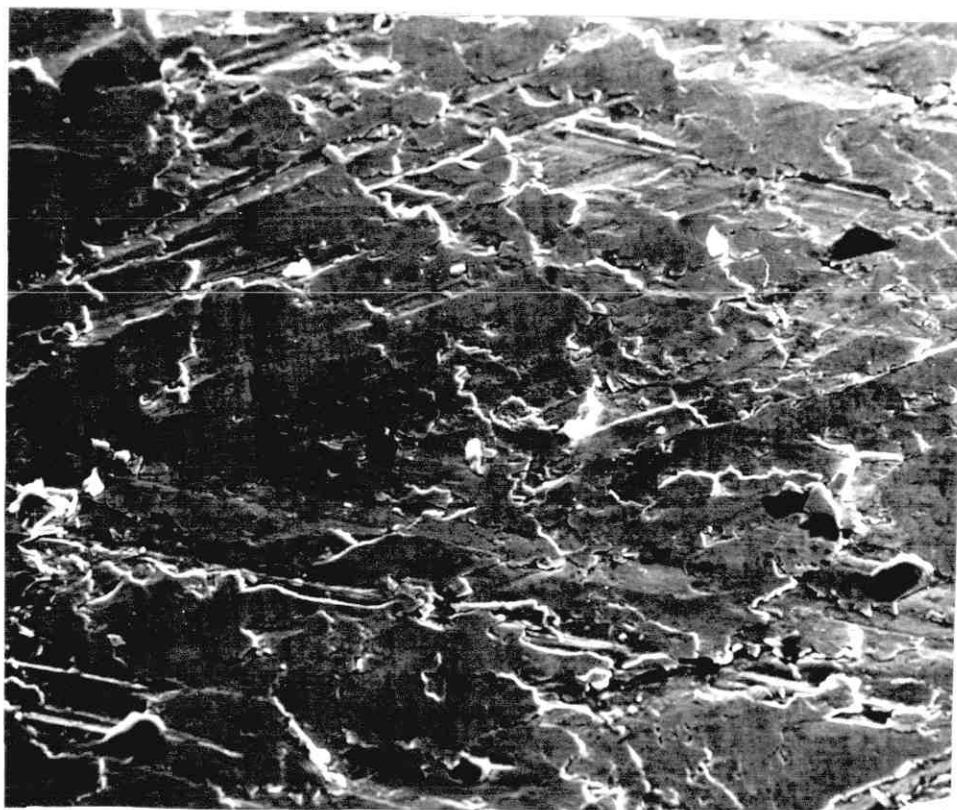


Figure 4.11 S.E.M. View of Liner with C5 at 300°C (immersed)  
(500x)



Figure 4.12 S.E.M. View of Liner with C5 at 200°C (immersed) (500x)

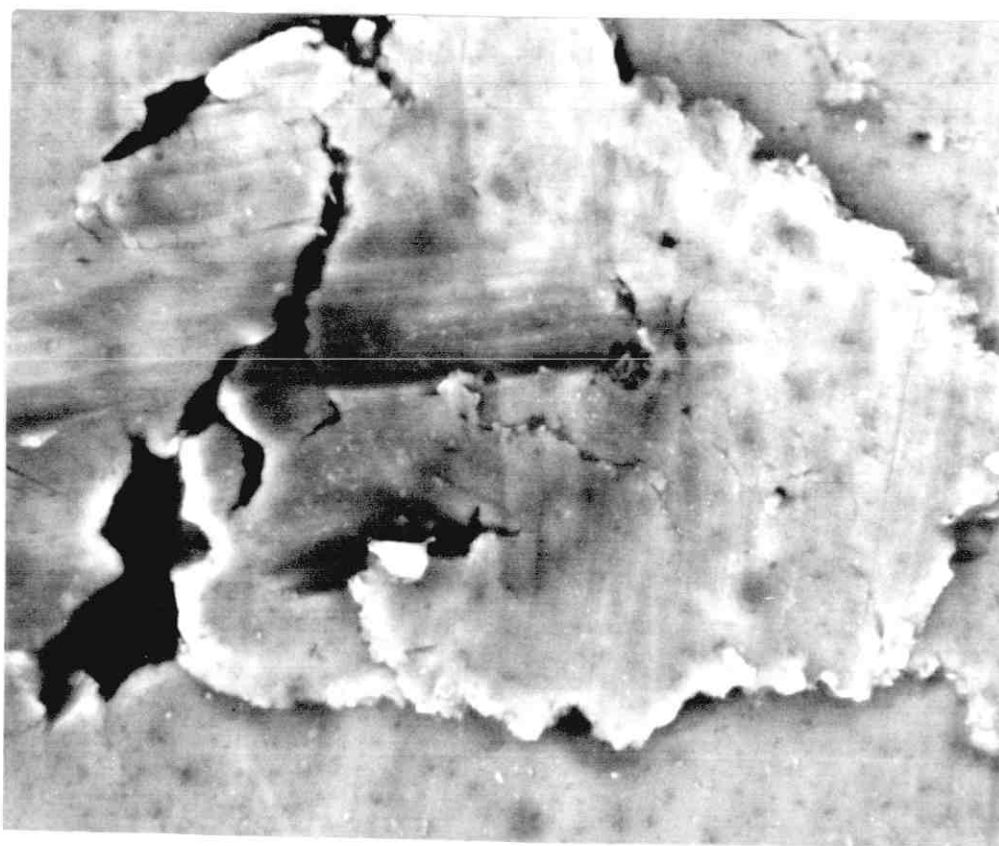


Figure 4.13 S.E.M. View of Liner with C2 at 300°C (immersed). (5000x)

on the heavily polished surfaces. This would indicate a higher level of plastic deformation on these surfaces, since this is consistent with the theory of delamination wear ( 7 ).

- 5) Figure 4.8 shows evidence of some continuous shallow lines on the surface, similar in form to abrasive scratching. Continuous lines were particularly relevant to the heavier polished surfaces, and were seen in the sliding direction (top to bottom).

#### 4.3.1.3 Micro-sectioning

In order to investigate changes in the microstructure between heavily polished and lightly polished liner specimens a number of micro-sections were prepared.

Figure 4.14 shows an untested liner specimen, which is taper sectioned, allowing a magnification of the subsurface by five times that of the overall photograph magnification. Figure 4.15 shows a taper section of the heavily polished H.F.R. liner shown in Chapter 3 (p101). Both these liners are unetched, as are all the liners shown in this thesis, since it was found that the graphite structure was more clearly defined without etching. A comparison of these two photographs indicates that for the polished H.F.R. liner specimen there is evidence of cracking around the graphite flakes, in some cases forming a semi-continuous crack. This observation will be confirmed by subsequent microstructural studies, these two photographs are included for reference.

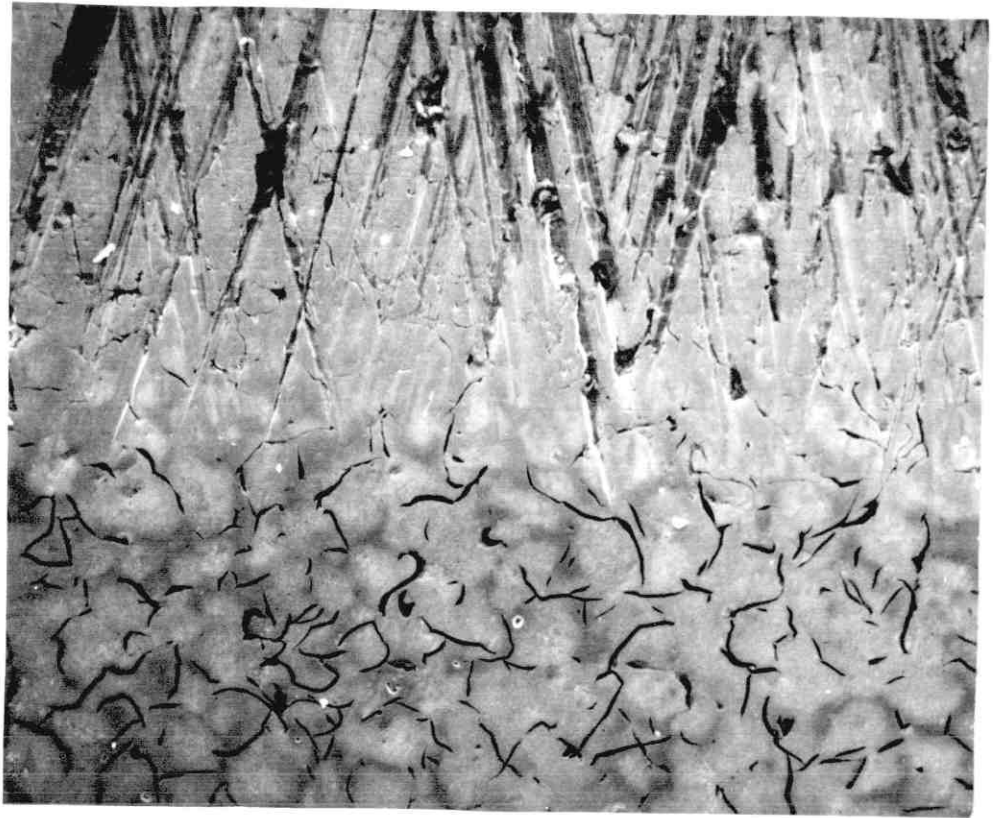


Figure 4.14 Axial Taper Micro-section of Untested Liner.  
(100x)



Figure 4.15 Axial Taper Micro-section of polished  
H.F.R. Liner. (100x)



Figures 4.16 and 4.17 are representative of the study of microstructures of H.F.R. liners taken from immersed contact commercial oil tests. Figure 4.16 shows no evidence of cracking whilst figure 4.17 shows extensive cracking around the tips of the graphite flakes, particularly in the top 200 $\mu$ m. These micro-sections are transverse i.e. sliding direction is into the photograph.

The subsurface cracking was observed on only the heavily polished liners (as in this case, C2 (45%). This indicates that heavily polished liners are highly stressed whilst low polished liners are not so. There is clearly no evidence of a white layer or glaze and furthermore no evidence of 'filling-in' of honing pattern as described by Sreenath and Ramon ( 35 ).

These observations clearly indicate that heavy polishing is a high stress phenomenon with liner material being probably removed rather than smeared in the sliding direction.

#### 4.3.1.4. Microprobe Analysis

As mentioned on page ( 89 ) a microprobe analysis (m.p.a.) was conducted to determine the chemical nature of the H.F.R. liner surfaces as well as identifying the composition of ferrogram particles. This section describes the results of the m.p.a. carried out on the immersed contact test liners lubricated with the commercial oils.



Figure 4.16 Transverse Micro-section of Liner with  
C1 at 200°C (immersed). (200x)

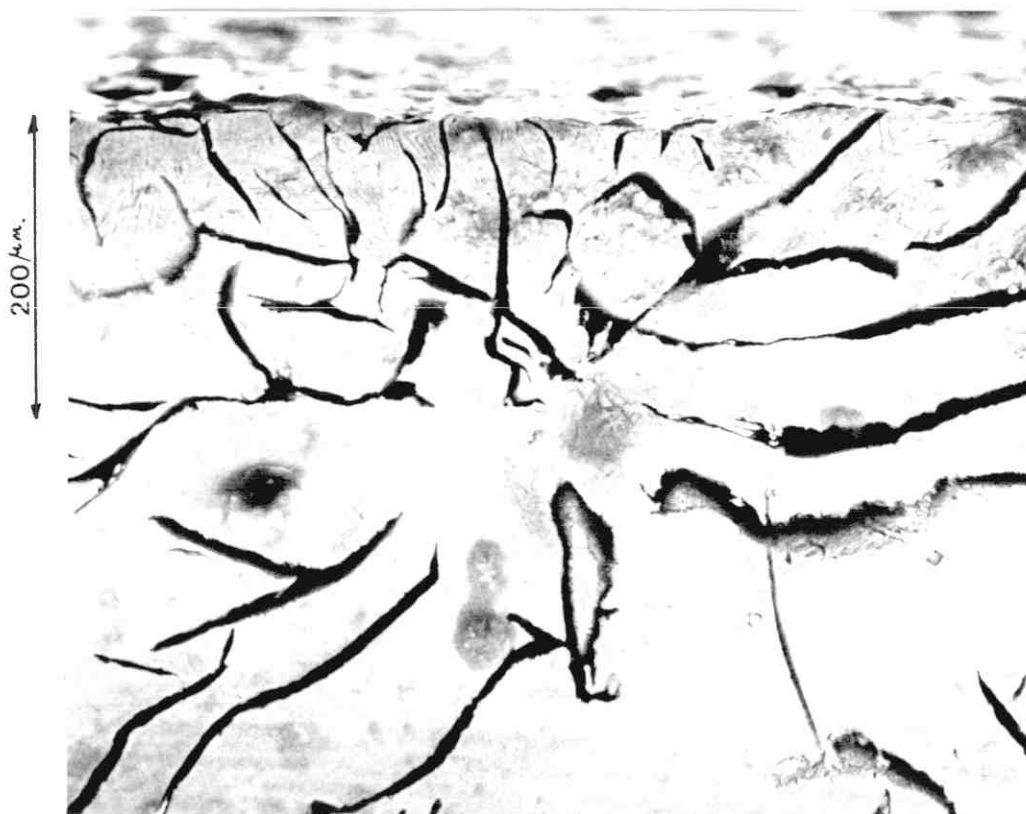


Figure 4.17 Transverse Micro-section of Liner with  
C2 at 200°C (immersed). (200x)



A brief description of the technique is given on page ( 86 ) and more detail is given in the review paper by Buckley ( 56 ) and also the book by Phillips ( 57 ). The count rate was greatly affected by the position of the x-ray detector and although a count time of 10 minutes for each plot was considered adequate, variations in the height of reference peaks (e.g. Iron) were considered to be due to positioning of the detector.

A series of plots were obtained for untested H.F.R. liner specimens and also for unworn areas of run H.F.R. liners. Figures 4.18, 4.19 are respectively representative of these and are included for reference. These plots are area analyses.

For each of the wear scars examined in this section two important points were observed:

- 1) Both spot and area analyses of the surfaces of each H.F.R. liner revealed very little variation from the background count shown in figure 4.19.
- 2) A spot analysis of cavities in the wear scar surface did reveal variations, as seen in figure 4.20. In this figure the ratio of sulphur to silicon peak heights is shown for each oil, since this was considered to be more representative than a plot of sulphur peak height for each oil. Figures 4.21, 4.22 are representative of this

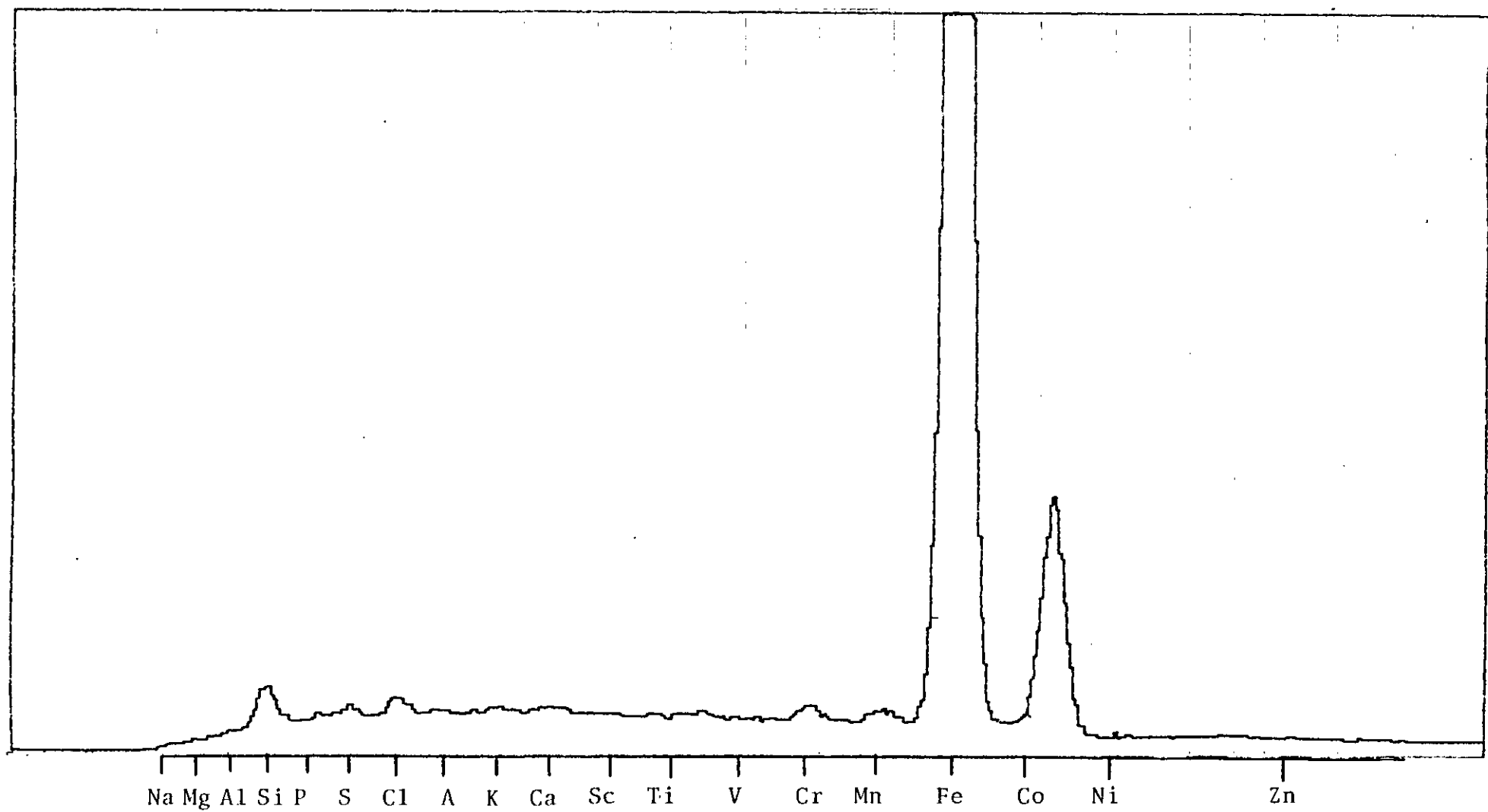


Figure 4.18 M.P.A. of Untested Liner (area)

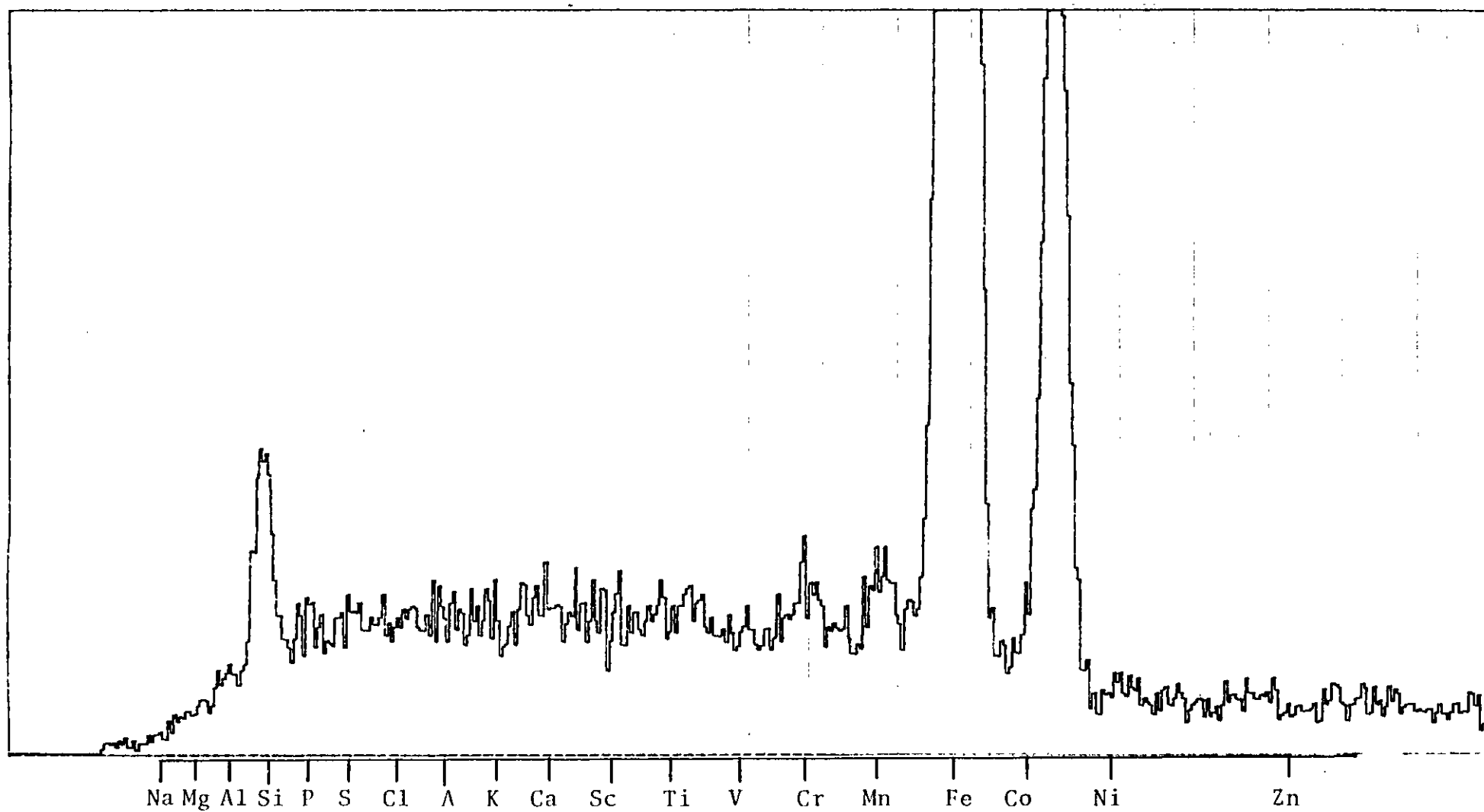


Figure 4.19 M.P.A. of Tested Liner, Not Wear Scar (area)

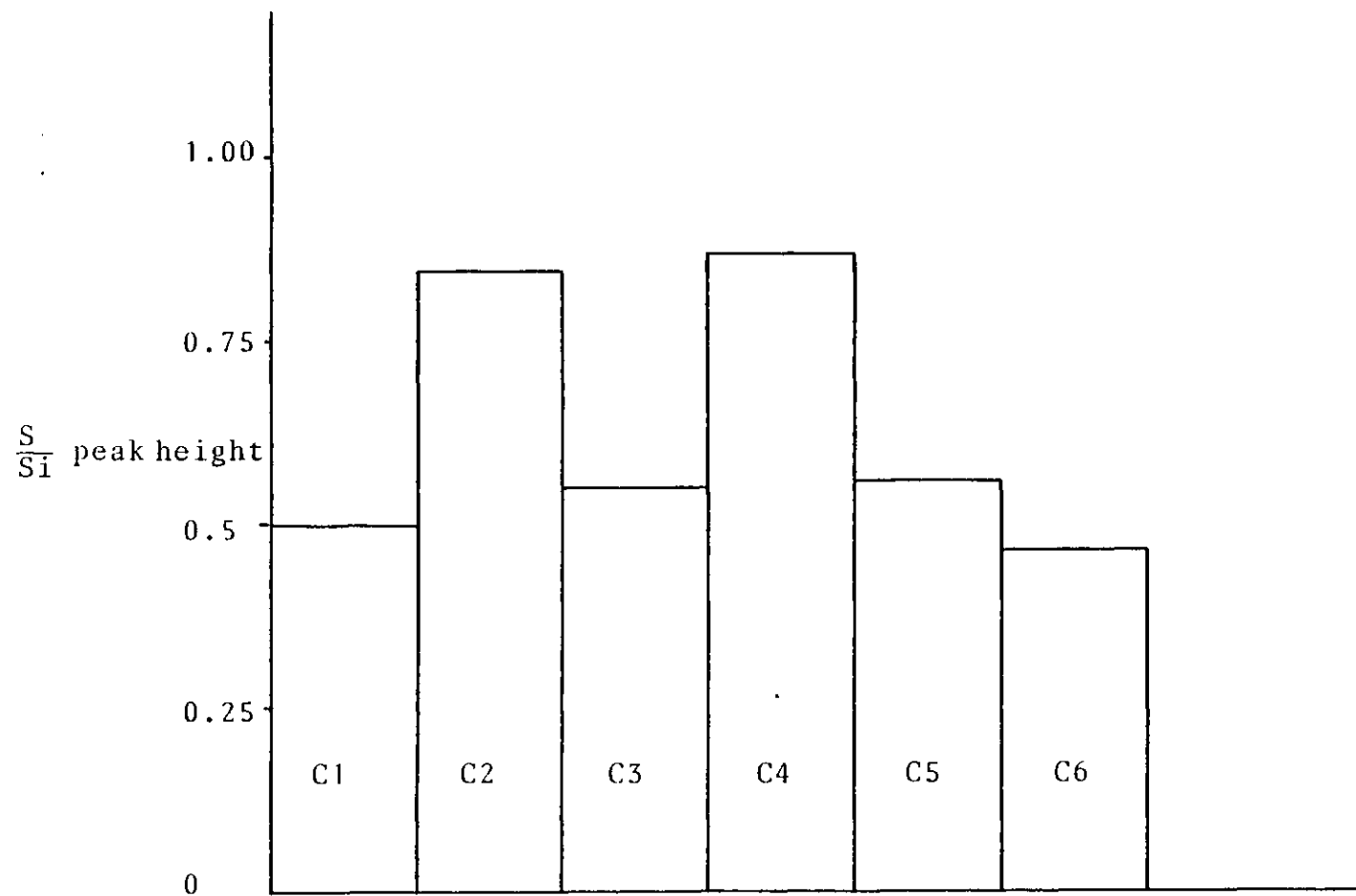


Figure 4.20 Ratio of  $\frac{S}{Si}$  Peak Heights for Each Oil

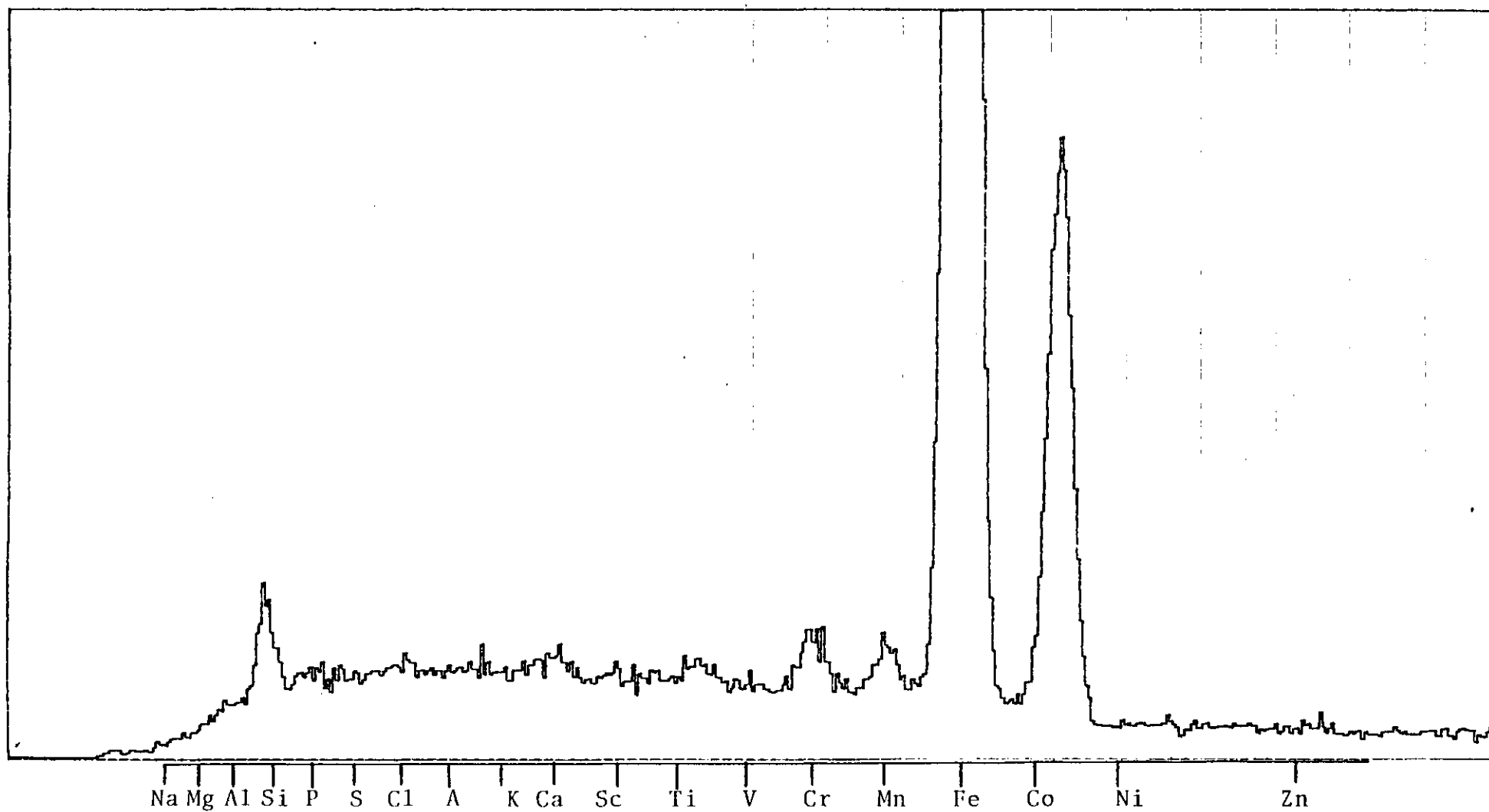


Figure 4.21 M.P.A. of Liner Cavity with Cl at 250°C (spot)

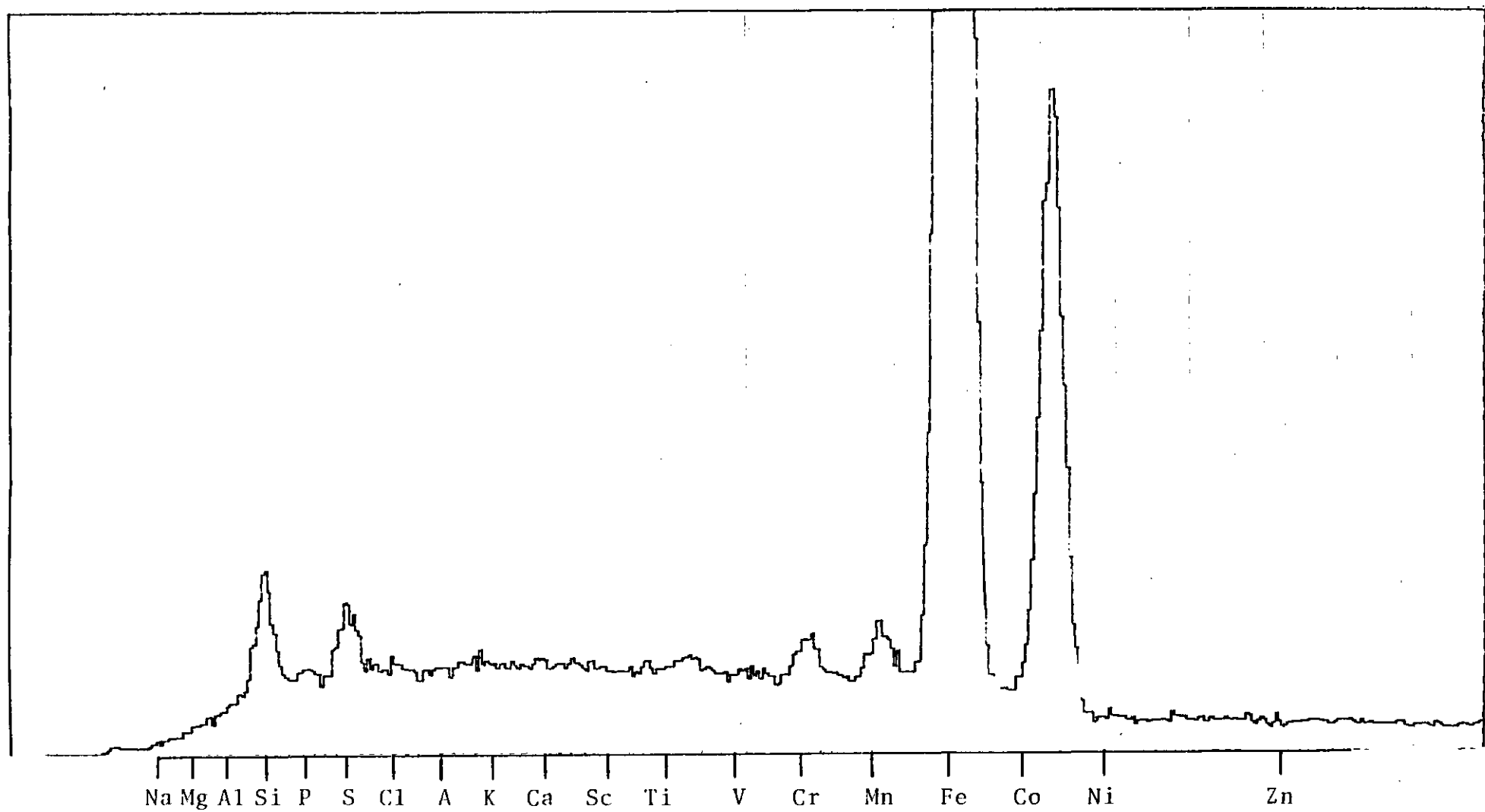


Figure 4.22 M.P.A. of Liner Cavity with C2 at 250°C (spot)

investigation. For heavily polished liner cavities a detectable sulphur trace was observed. A review of literature on this subject confirms that sulphur seems associated with cavities on heavily polished liner surfaces and not on non-polished surfaces ( 62).

Coy and Quinn ( 63 ) also found sulphur associated with smooth load bearing areas of specimens taken from a 4 ball machine and conclude that the E.P. activity is attributable to small amounts of iron sulphide. The results of the analysis in this section may indicate that polishing is more associated with E.P. action than antiwear action. In particular it is possible that the formation of an iron sulphide film and its continual removal, as described by Mills and Cameron ( 27 ), is partly responsible for the smoothening of the surface. In this respect a chemical corrosive wear process could be partly responsible for the smoothening of the surfaces, with abrasive particles also being formed. This idea is further supported by Forbes ( 64 ) who also identified sulphur with load carrying areas. This will be discussed in more detail in section 4.4 and finally in Chapter 6.

#### 4.3.2 Drip feed tests

##### 4.3.2.1 Pen recorder data

For the 200<sup>0</sup>C tests each lubricant attained a

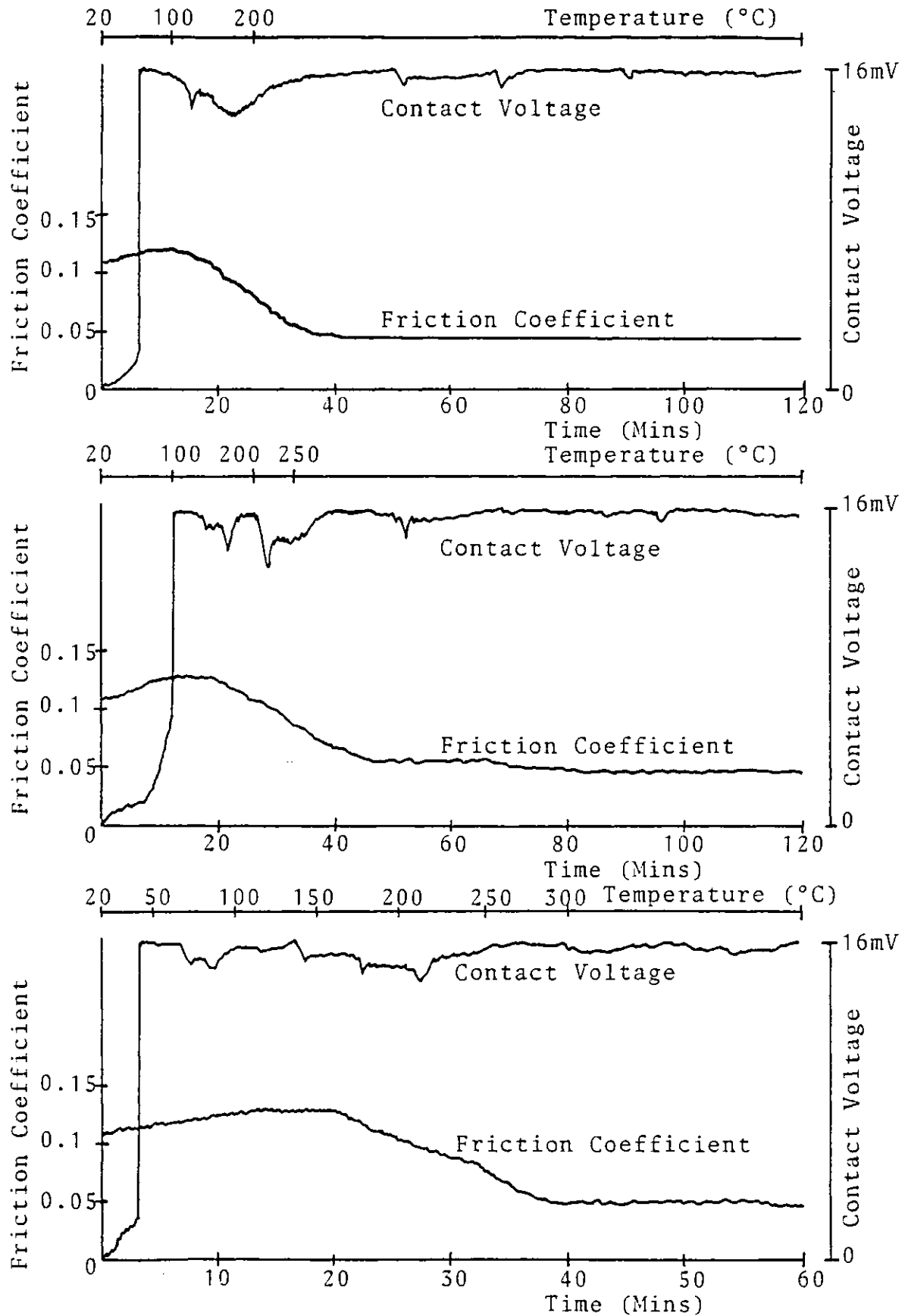


FIGURE 4.23 C1 at 200°C, 250°C, 300°C (drip feed)



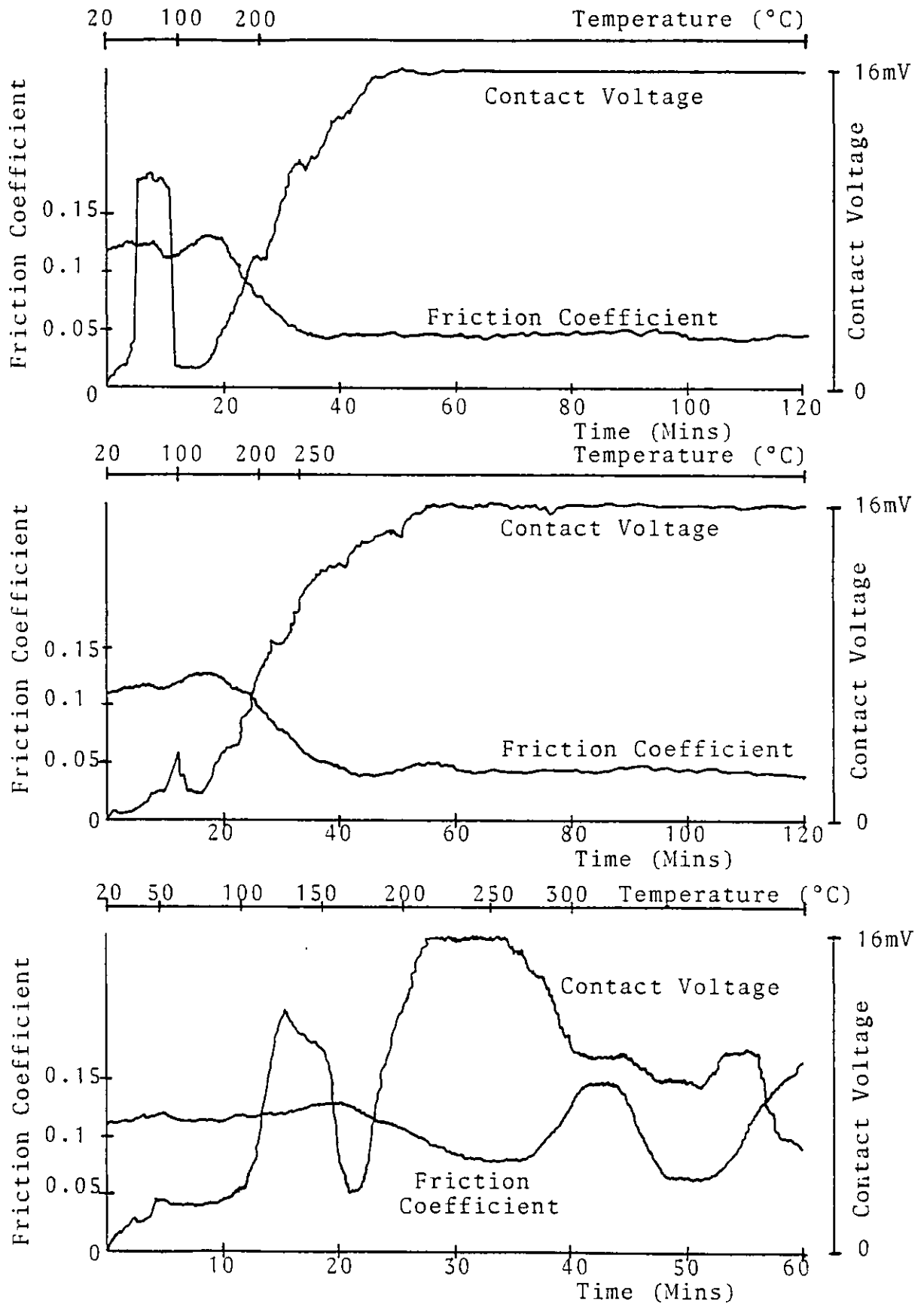


FIGURE 4.24 C2 at 200°C, 250°C, 300°C (drip feed)

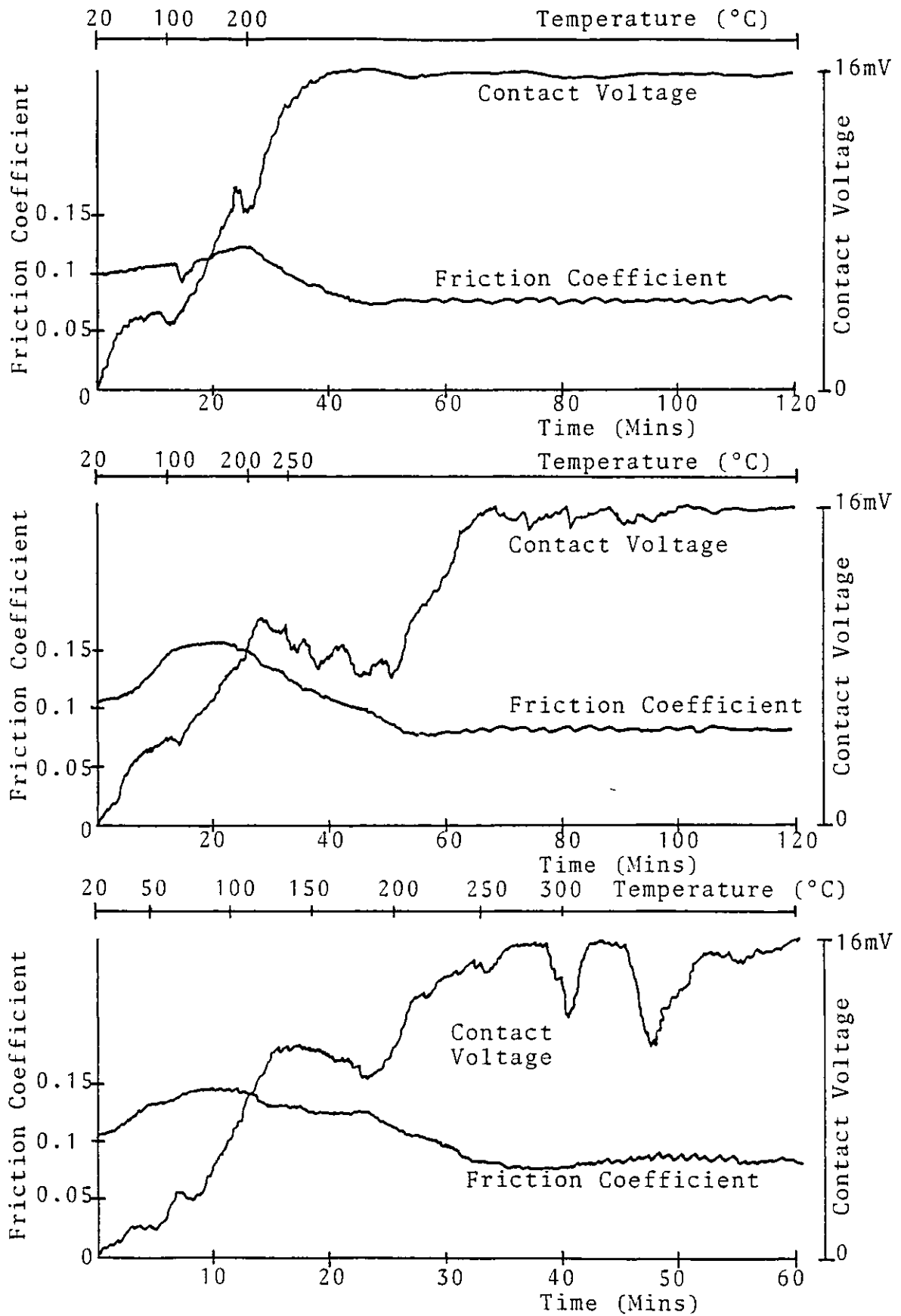


FIGURE 4.25 C3 at 200°C, 250°C, 300°C (drip feed)

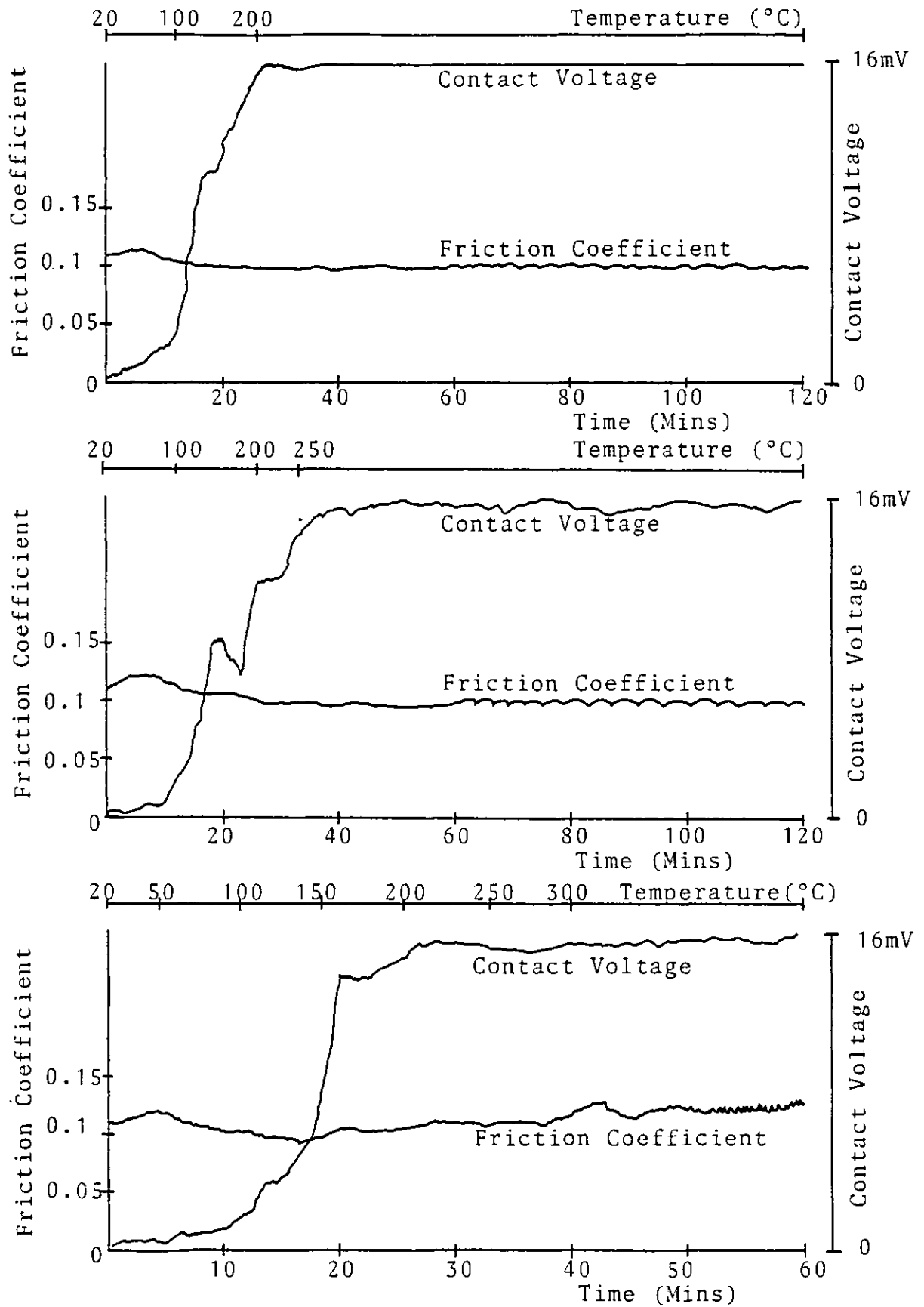


FIGURE 4.26 C4 at 200°C, 250°C, 300°C (drip feed)

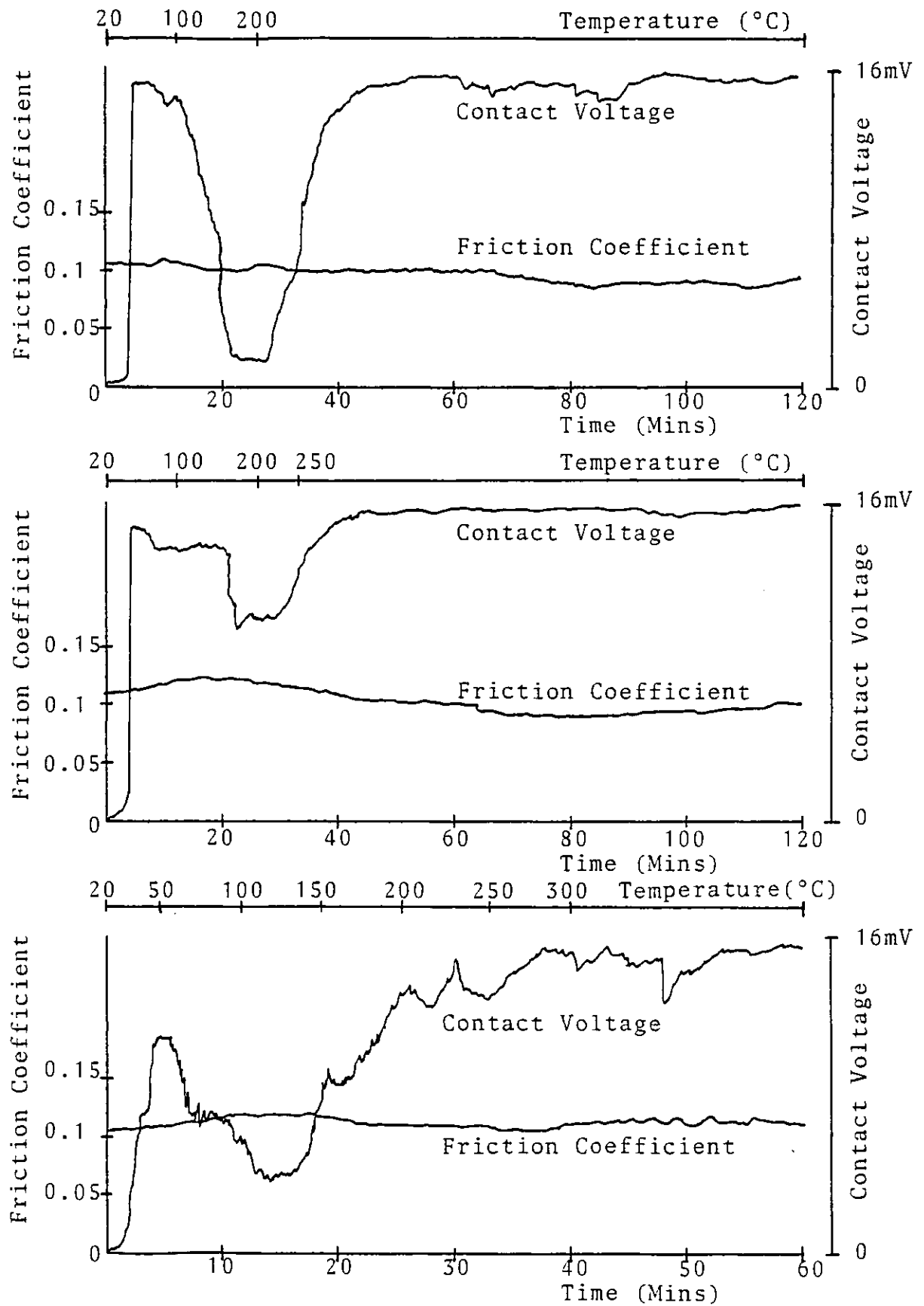


FIGURE 4.27 C5 at 200°C, 250°C, 300°C (drip feed)

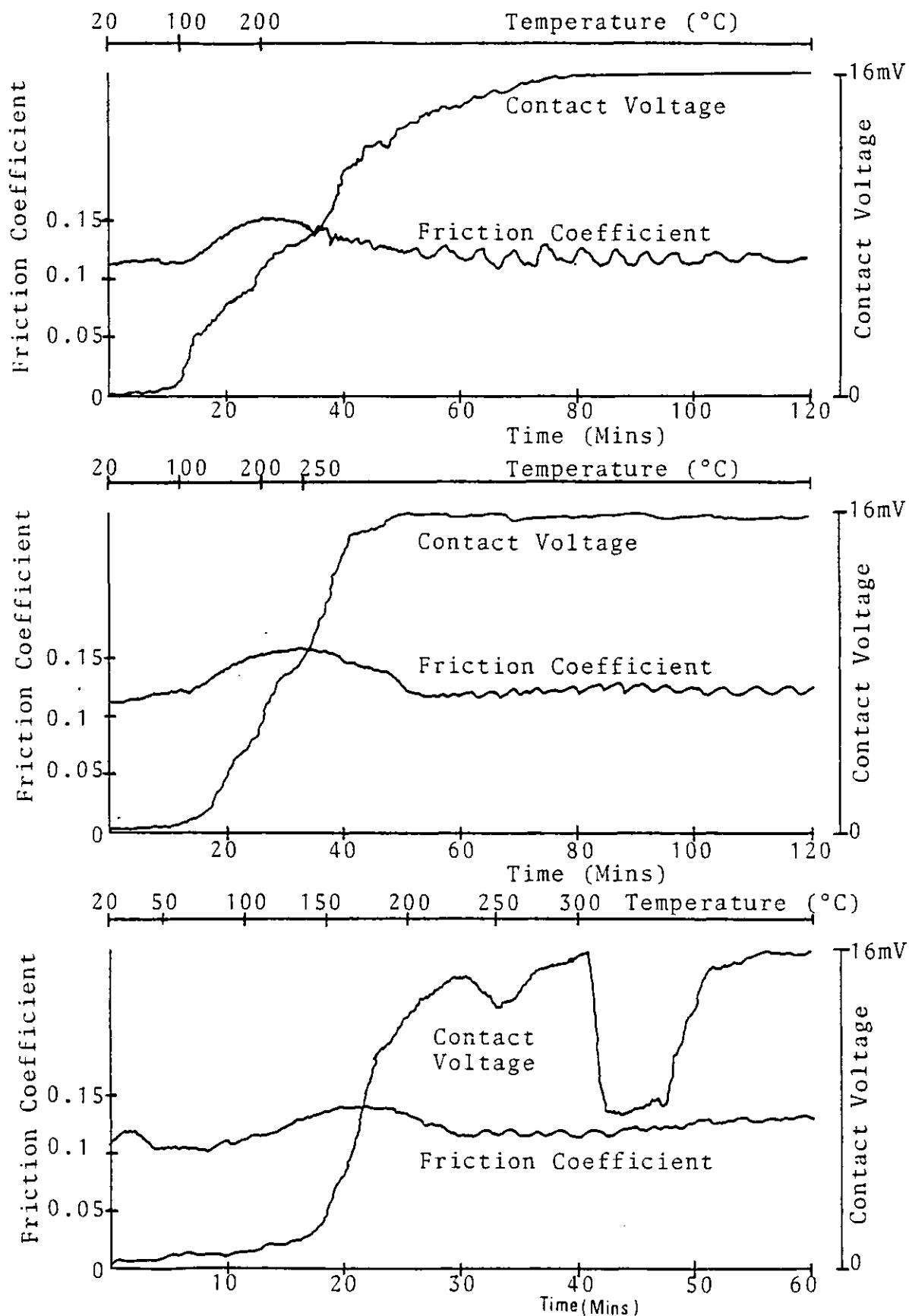


FIGURE 4.28 C6 at 200°C, 250°C, 300°C (drip feed)

stable thick boundary oil film. The friction coefficient trace was stable for each oil, particularly for C1, with the exception of C6. C6 exhibited the 'saw tooth' profile observed in a few of the previous tests.

In the 250°C tests the contact voltage and friction coefficient traces are almost identical for each oil as the 200°C test. Oil C4 showed a more pronounced 'saw tooth' profile whilst that of C6 was less pronounced.

For the 300°C tests most oils showed a thick boundary film for a portion of the test. C1 was the best and C4 the worst in this respect, with C1 maintaining a high contact voltage for 18 minutes longer than C4. The friction trace of oil C2 is very erratic and unstable and bore polishing is likely to have occurred. Oil C4 shows a tendency for the friction trace to become unstable and increase. The friction traces of the oils C1, C3, C5 and C6 are more stable than C2 and C4.

#### Deductions

- 1) For each oil tested it was observed that the oil film did not collapse, even at high temperature. The friction coefficient became slightly unstable at high temperatures, particularly for C2.

2) Oils C2 and C4 had an increasing friction coefficient for the 300°C test, whereas the other oils had only slight instability at high temperature.

3) It is not possible to rank the oils in terms of bore polishing severity from the pen recorder results. It is clear, however, that oils C2 and C4 gave results which would indicate a high wear rate.

#### 4.3.2.2 Visual S.E.M.

Figures 4.29 to 4.34 are representative of visual S.E.M.s of drip feed test liner surfaces. Again a number of points are evident.

- 1) A good correlation between engine tests and bench tests was obtained. It is clear that liner surfaces with C2 (45%)(figure 4.29 and C4 (55%)(figure 4.30) are much smoother than the other liner surfaces (e.g. figure 4.31). Again the engine tests identified these as the oils likely to produce heavy polishing.
- 2) The effect of temperature upon the severity of polishing is illustrated by a comparison of figures 4.32, 4.33. Figure 4.32 although illustrating some flattening of the surface has a more clearly defined honing pattern than figure 4.33. There is



Figure 4.29 S.E.M. View of Liner with C2 at 250°C (Drip Feed)  
(200x)

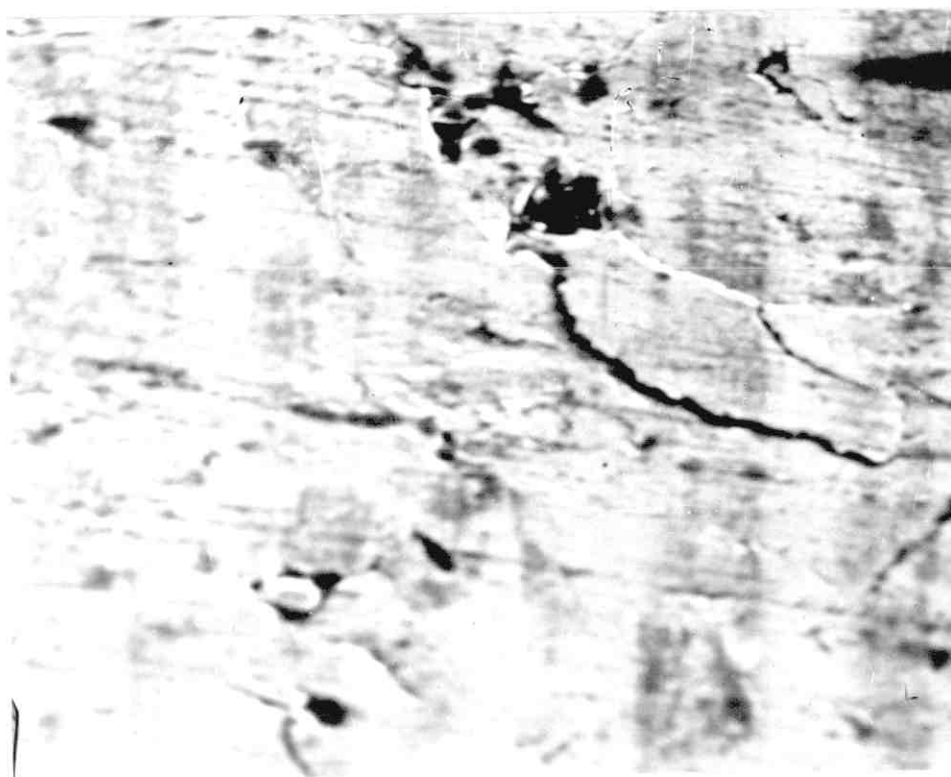


Figure 4.30 S.E.M. View of Liner with C4 at 250°C (Drip Feed)  
(200x)





Figure 4.31 S.E.M. View of Liner with C1 at 250°C (Drip Feed)  
(200x)



Figure 4.32 S.E.M. View of Liner with C3 at 200°C (Drip Feed)  
(1000x)

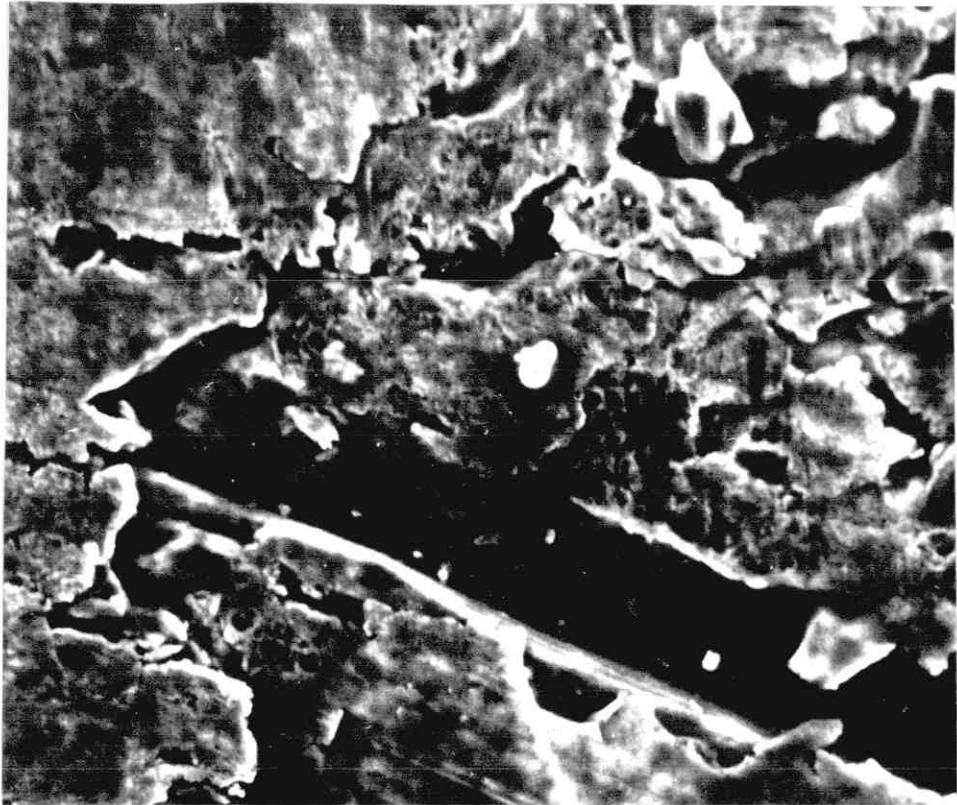


Figure 4.33 S.E.M. View of Liner with C3 at 300°C (Drip Feed)  
(1000x)

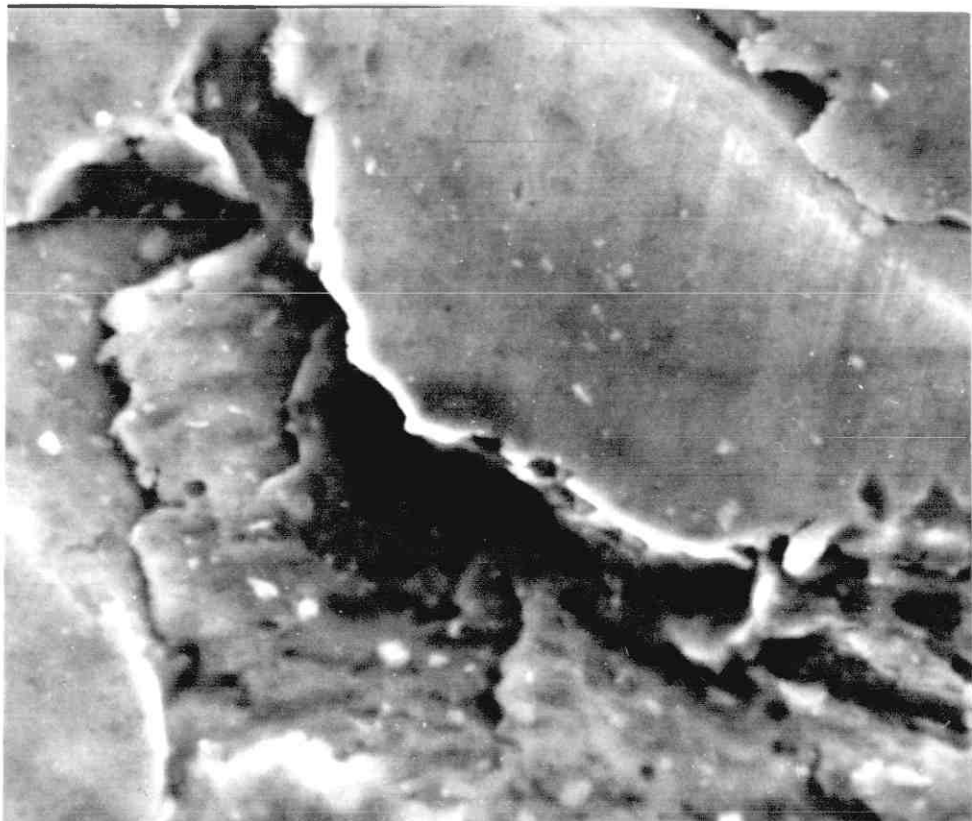


Figure 4.34 S.E.M. View of Liner with C4 at 300°C (Drip Feed)  
(2000x)

some evidence of possible corrosive pitting in the centre of figure 4.33.

The effect of inclining the apparatus appears to be a slight decrease in the amount of surface smoothening. This is illustrated by a comparison of figures 4.10 and 4.31.

However the correlation with engine tests does not appear to be altered.

3) Further evidence of plastic deformation can be seen in figures 4.29, 4.32 and 4.33. Figure 4.30 shows a smooth surface although it is not clear whether this is by 'filling-in' of the honing lines or by removal of material. This will be investigated in the next section.

4) Figure 4.34 is a high magnification view of a possible delamination wear particle. This is seen lifting up against the sliding direction (top to bottom). The existence of such particles is again discussed in section 4.3.2.5.

As in section 4.3.1 these particles were detected on the heavily polished specimens only and were thought to be indicative of highly stressed areas, consistent with the Delamination theory of wear.

5) There was little evidence of abrasive scratching

on the H.F.R. liner surfaces. Figure 4.29 shows some fine scratches, although these are not as deep or continuous as those seen in the corresponding immersed test (Figure 4.8).

#### 4.3.2.3 Micro-sectioning

Figures 4.35, 4.36 represent the liner subsurfaces seen with the drip feed commercial oil H.F.R. tests.

Figure 4.35 again shows that, although there is some subsurface cracking, this is not extensive for lightly polished liners. However figure 4.36 shows a semi-continuous crack formed between the tips of the graphite flakes, which is typical of that observed for all highly polished H.F.R. liners. The cracking is far more extensive for the highly polished liner, and again indicates that heavy polishing is a high stress phenomenon. There is no evidence of white layer formation, glaze formation or 'filling-in' of honing pattern as described by various authors.

In order to compare these results with practice, two liners from a Ford Tornado engine were sectioned. Figure 4.37 shows very little evidence of subsurface cracking or deformation, and this agrees with low polishing tests seen with H.F.R. liners. Figure 4.38 shows extensive subsurface cracking to a depth greater than that seen with the H.F.R. tests. Both these photographs indicate that bore polishing is a high



Figure 4.35 Axial Micro-section of Liner with  
C6 at 250°C (Drip Feed). (200x)



Figure 4.36 Axial Micro-section of Liner with  
C4 at 250°C (Drip Feed). (200x)



Figure 4.37 Axial Micro-section of Unpolished Ford Tornado Liner. (200x)



Figure 4.38 Axial Micro-section of Polished Ford Tornado Liner. (200x)

stress phenomenon, since cracking is observed around discontinuities in the cast iron matrix of the more highly stressed liners. These sections are axial i.e. sliding direction left to right.

There is clearly a good correlation between the polishing phenomenon observed in H.F.R. tests and that achieved in highly polished Ford Tornado liners.

#### 4.3.2.4 Microprobe analysis

As in section 4.3.1.4 an analysis of the liner surfaces was conducted, and the same correlation between cavities on polished surfaces and sulphur content was observed. This is illustrated in Figure 4.39 Figures 4.40, 4.41 represent the m.p. analysis where there is no evidence of sulphur for C3 (15%, unpolished) whilst C4 (55%, polished) again shows a distinct sulphur peak. This was considered to indicate that the formation of an iron sulphide film and its removal by the piston ring could constitute a corrosive wear process. This could lead to a gradual smoothing of the surface by chemical corrosion as mentioned by Barcroft (65) and also initiate abrasive particles which could in turn cause smoothing of the surface.

In order for a comparison to be made with the Ford Tornado test a series of analyses of heavily polished and lightly polished Ford Tornado liners were conducted. Again it was noticed that whilst there was no apparent difference between surface analyses

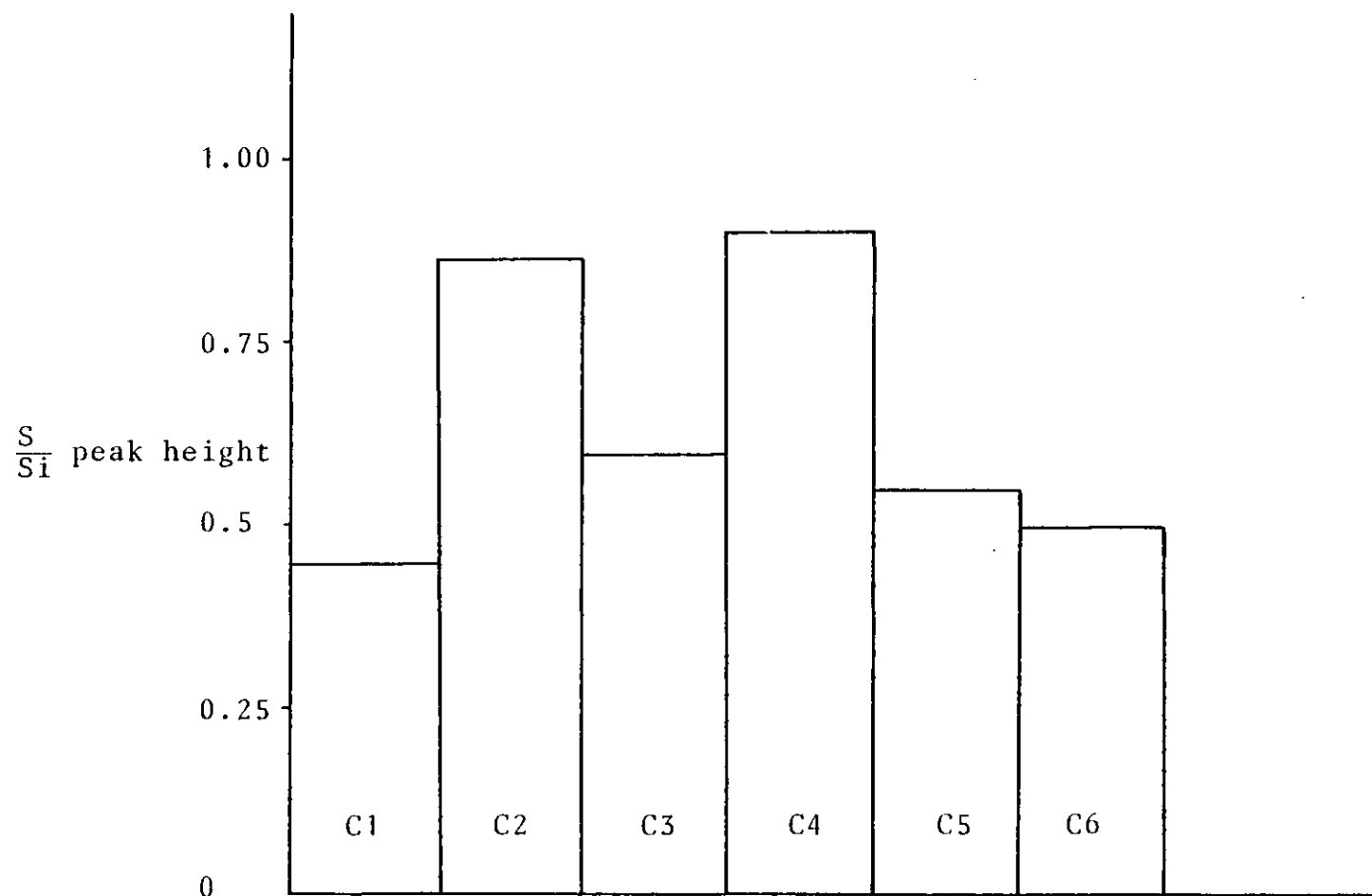


Figure 4.39 Ratio of  $\frac{S_i}{S_1}$  Peak Heights for Each Oil



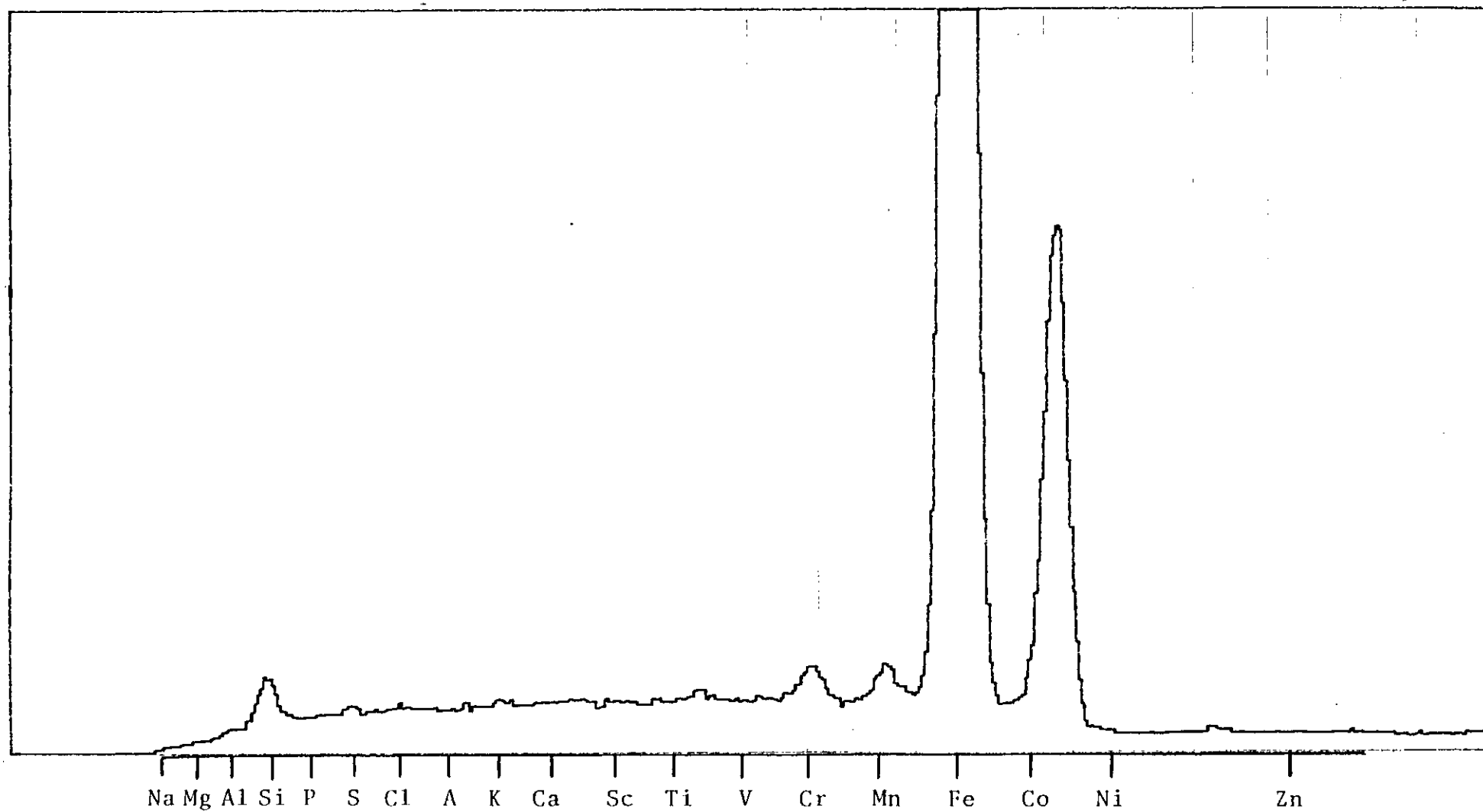


Figure 4.40 M.P.A. of Liner Cavity with C3at 200°C (spot)

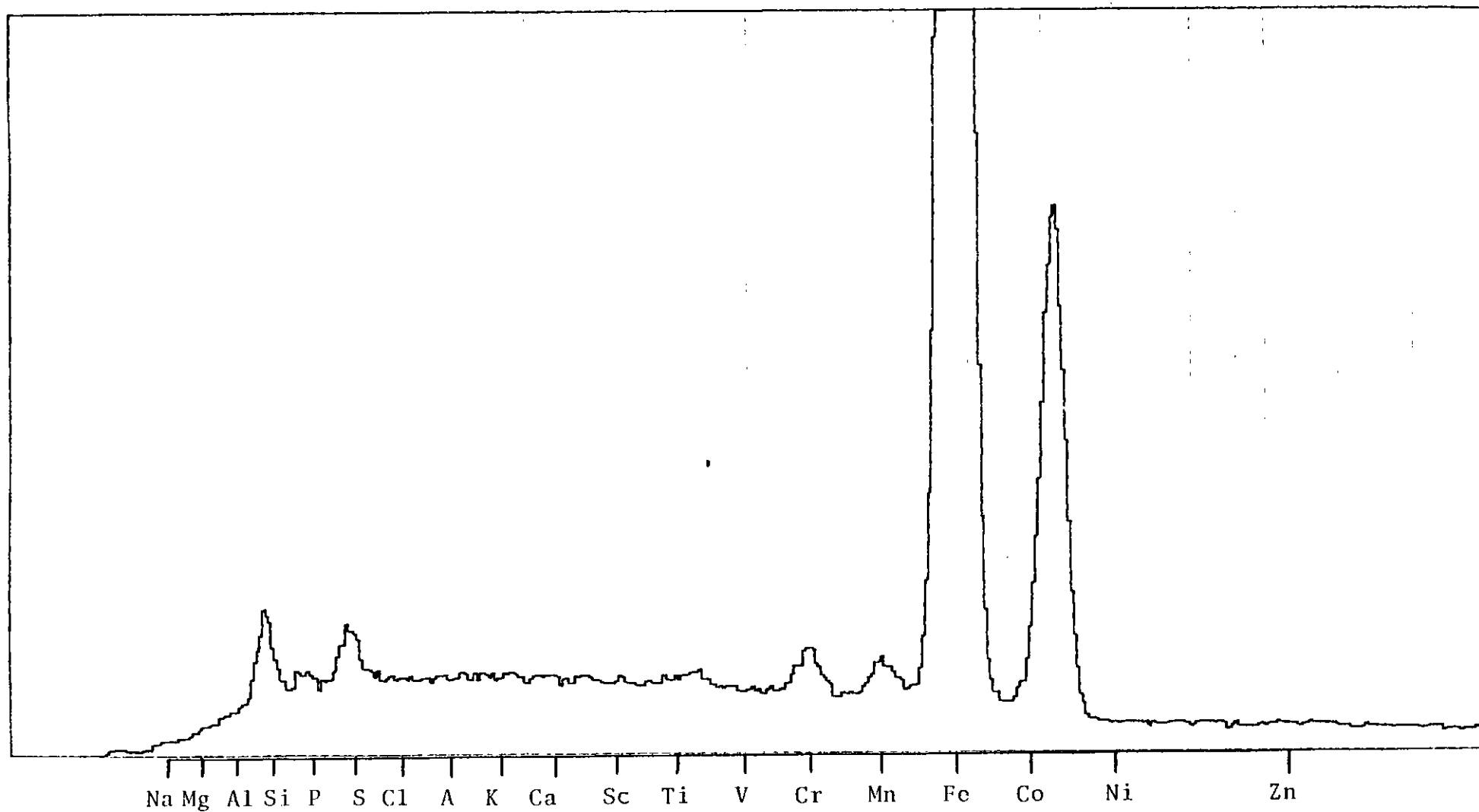


Figure 4.41 M.P.A. of Liner Cavity with C4 at 200°C (spot)

there was a difference between cavity analyses. Figures 4.42 and 4.43 are representative of this fact. Thus the correlation found between sulphur and heavily polished liner pits is confirmed in practice ( 62 ) and also with engine test liners. This will be further discussed in section 4.4.

#### 4.3.2.5 Ferrography

In order to gain further information on the possible wear mechanisms prevalent in this study a ferrographic analysis was conducted. The Duplex ferrograph was used in this context, as described on page ( 90 ). The results take two forms:

##### 1) Optical microscopy.

A study was made using a bichromatic microscope, as mentioned on page ( 92 ). Figure 4.44 is typical of the results. In this photograph a number of stringers of normal rubbing wear particles can be seen, similar to those seen in the Wear Particle Atlas ( 36 ) compiled by Bowen et al. The lubricant in this case was C1.

##### 2) Scanning electron microscopy

As mentioned previously (p 92) it was necessary for the glass slides to be made electro-conducting by plating with gold. It was found that, although

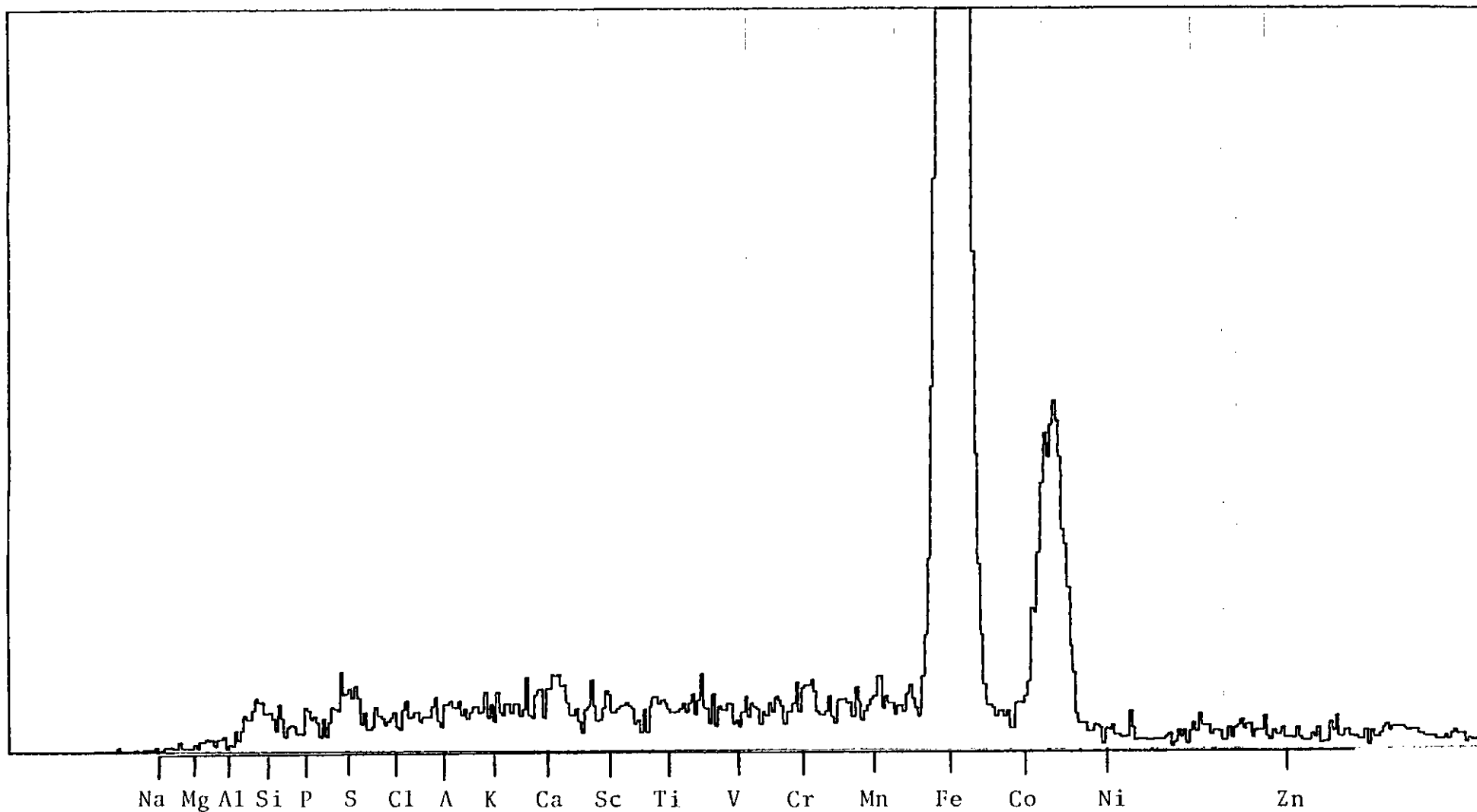


Figure 4.42 M.P.A. of Liner Cavity for Lightly Polished Ford Tornado (spot)

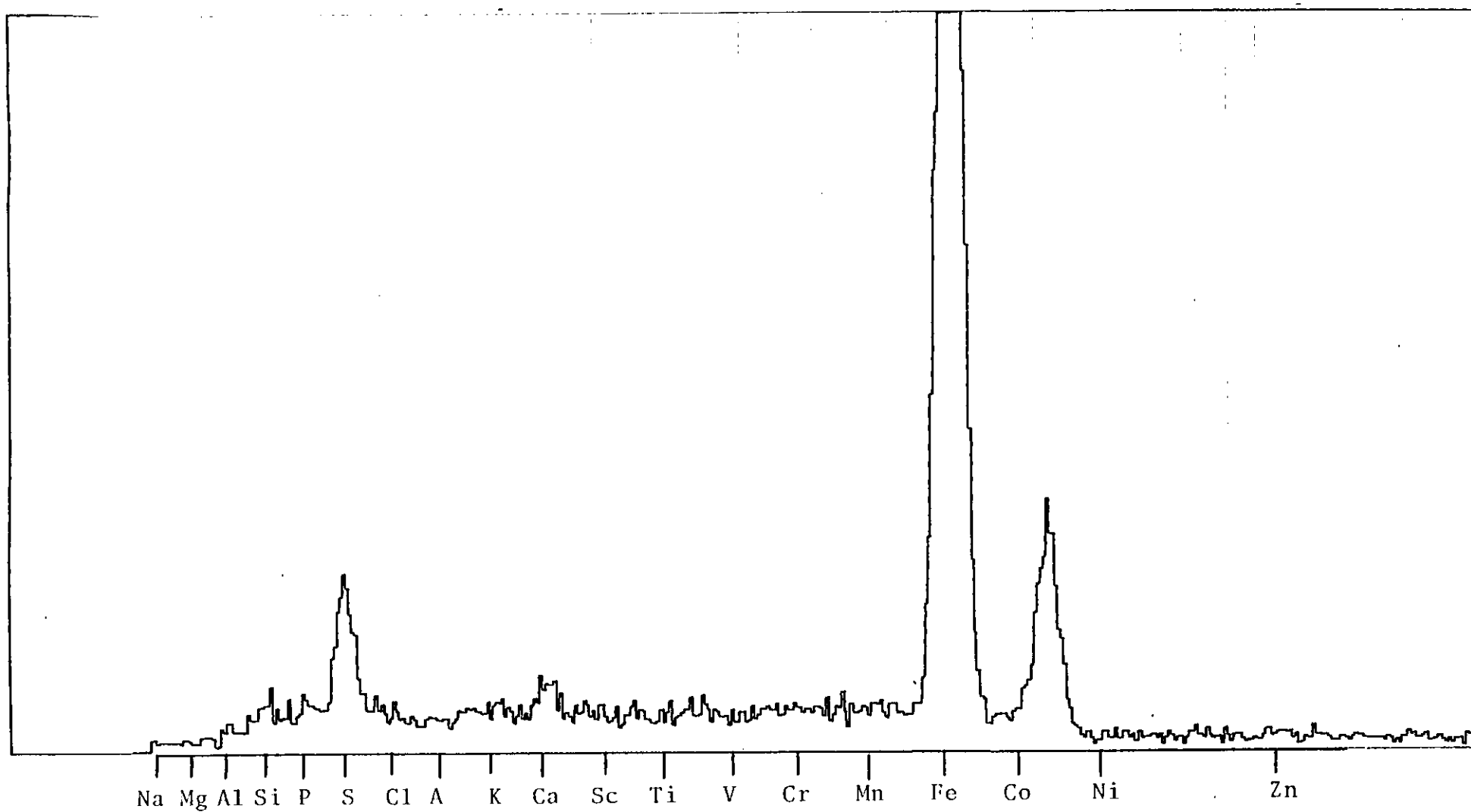


Figure 4.43 M.P.A. of Liner Cavity for Heavily Polished Ford Tornado (spot)

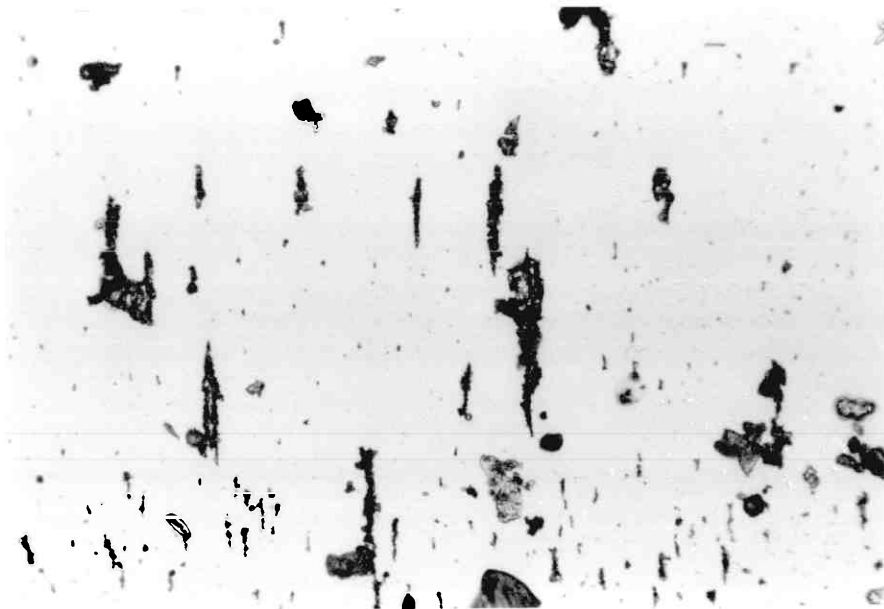


Figure 4.44 Optical View of Ferrogram. C1 at 200°C (Immersed)  
(220x)

the particles were visible on the slide, their composition was not clear i.e. iron based, oil degradation products and so on. In order to resolve this problem it was necessary to conduct a microprobe analysis of the particle under consideration. Figure 4.45 shows the typical background spectrum obtained when the glass slide was analysed. Clearly the constituents of the glass and the gold peak (far right) are visible with no trace of iron. Figure 4.46 shows the typical spectrum of an iron based particle with the iron peak superimposed upon the background spectrum.

Figures 4.47, 4.48 are typical of the S.E.M. analyses of ferrograph slides. Figure 4.47 shows a high magnification view of a thin sheet-like iron based particle. This is of similar size and shape to those seen on H.F.R. liner surfaces and confirms the existence of delamination wear. Figure 4.48 is a lower magnification view of a similar particle, again suggesting the likelihood of delamination wear. These were not observed with the non-heavy polishing oils, but only (as in these two photographs) with the heavy polishing oils.

#### 4.3.2.6 Zinc analysis

As mentioned earlier, it was hoped that by a zinc analysis of the commercial oils an estimation of the ZDDP concentration could be obtained. This was to test

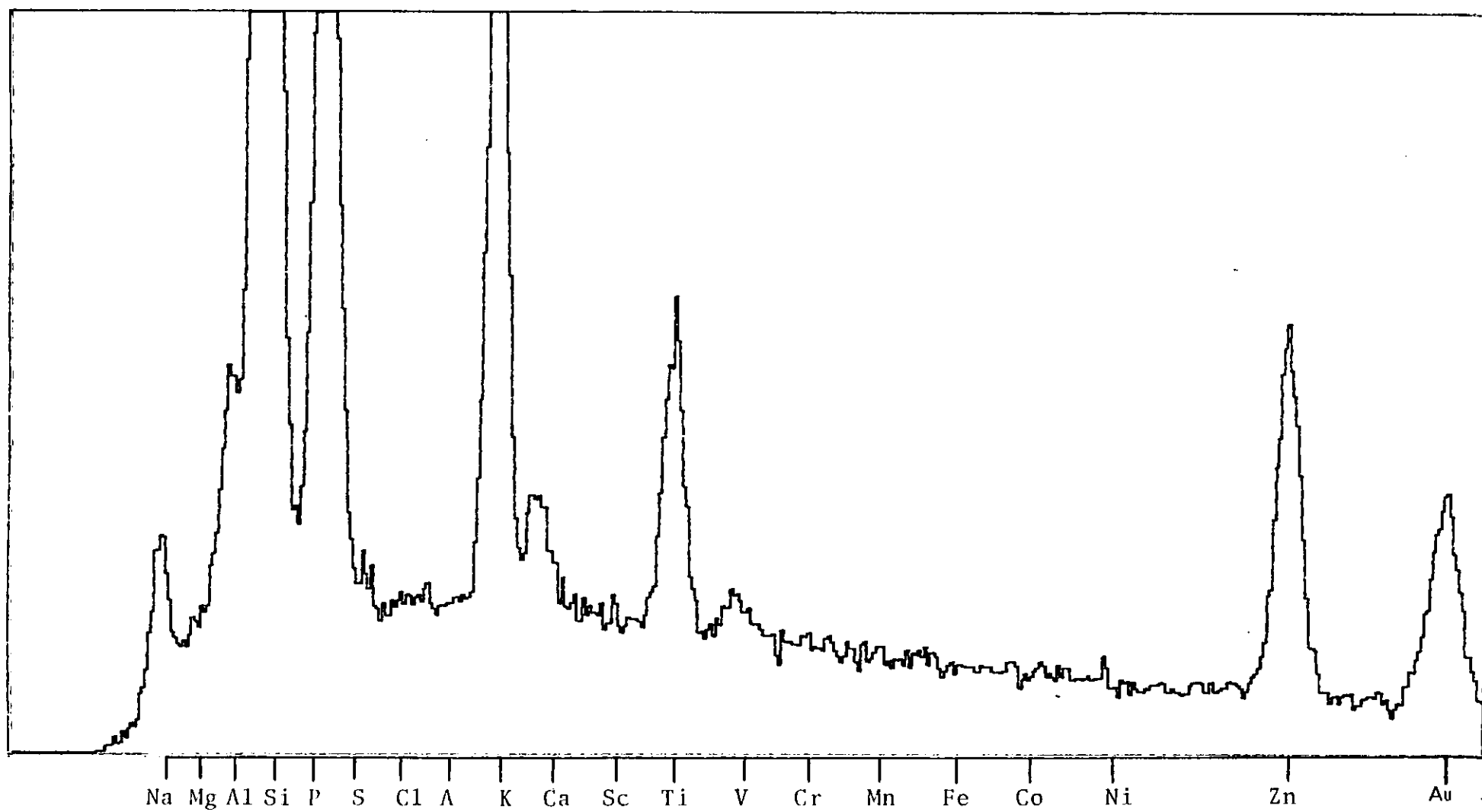


Figure 4.45 M.P.A. of Gold Coated Ferrogram Slide (spot)



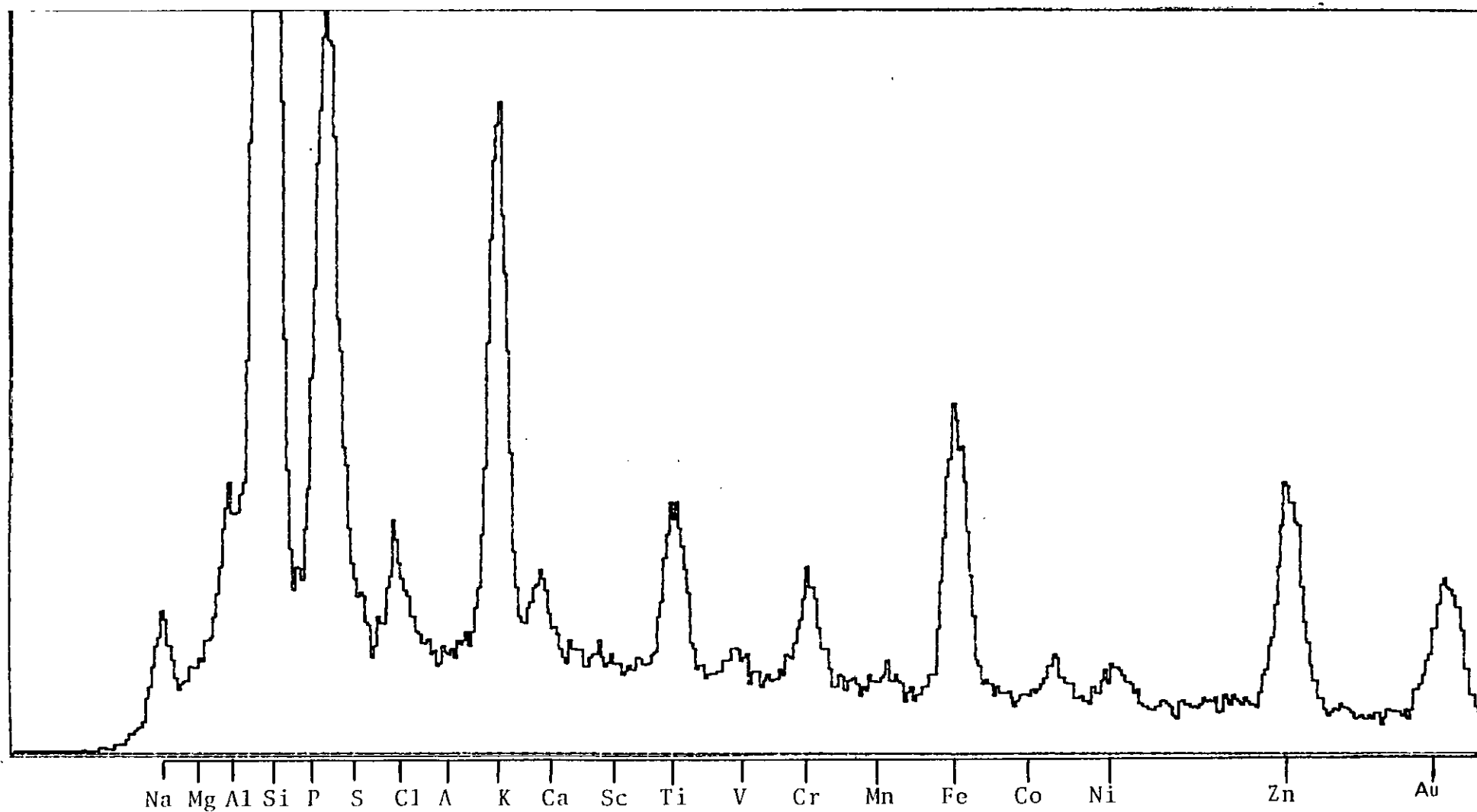


Figure 4.46 M.P.A. of Iron Containing Particle on Ferrogram Slide (spot)

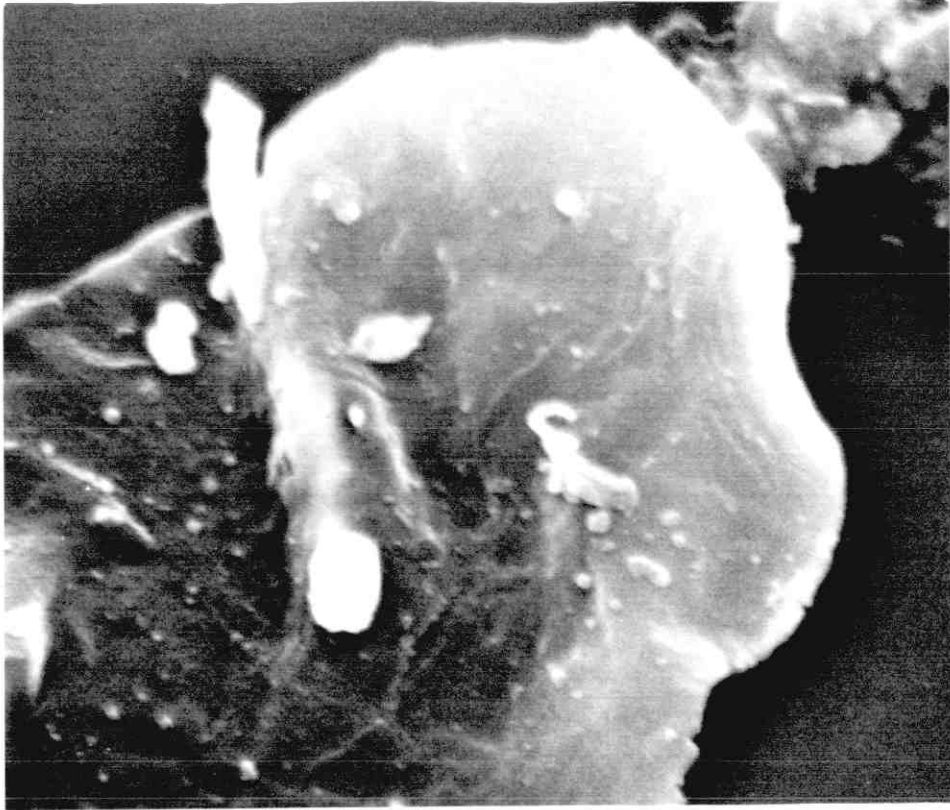


Figure 4.47 S.E.M. View of Ferrogram. C2 at 200°C (Drip Feed)  
(5000x)

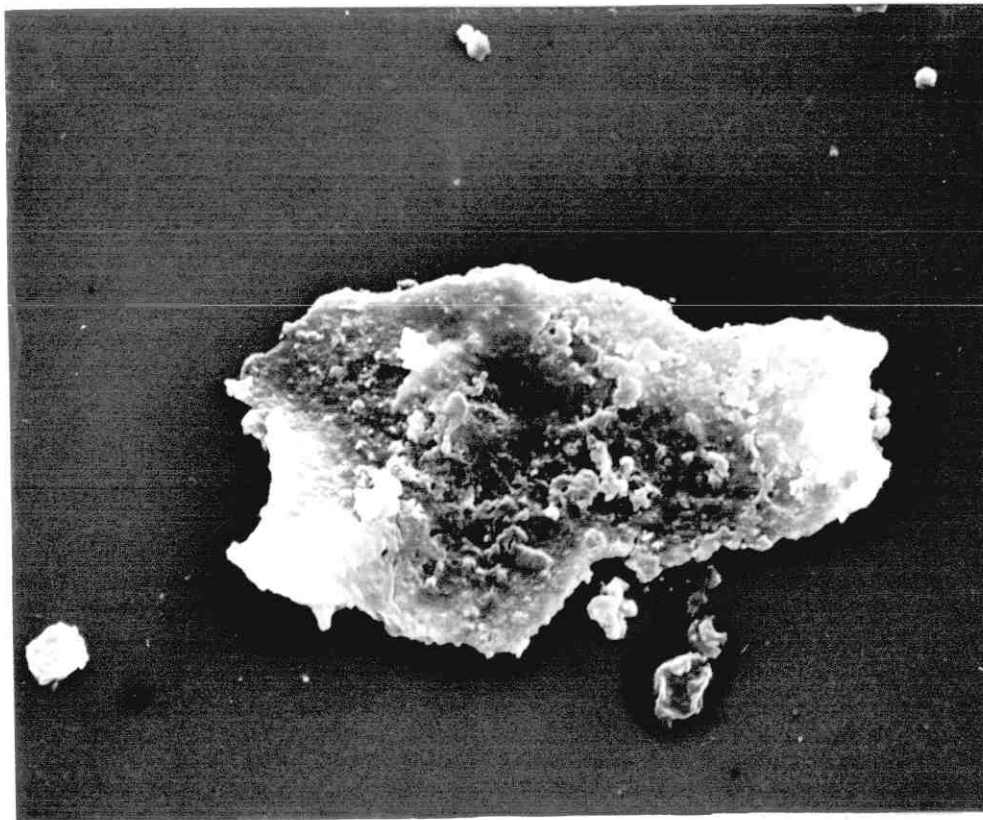


Figure 4.48 S.E.M. View of Ferrogram. C2 at 200°C (Drip Feed)  
(2000x)

for correlation between ZDDP concentration and the polishing percentages of each oil given by the Ford Tornado test.

0.5g of each test lubricant was carefully weighed out and then a range of acids (sulphuric, perchloric and nitric) added. The mixture was then slowly heated for 2 hours until a colourless liquid remained. This was then diluted with distilled water and analysed by atomic absorption spectroscopy. In this technique the required sample is burnt in a gas flame and the amount of absorbance detected by a special filament which relays the information to a pen recorder. As a means of checking that the procedure was correct two reference oils were used, these were concentrations of 0.2% and 2% of ZDDP, C, in a base oil, B2. The table below reveals the % Zinc ( $\frac{W}{W}$ ) detected in each oil.

| Oil         | % Zn ( $\frac{W}{W}$ ) |
|-------------|------------------------|
| B2 + 0.2% C | 0.02                   |
| B2 + 2% C   | 0.196                  |
| C1          | 0.120                  |
| C2          | 0.154                  |
| C3          | 0.124                  |
| C4          | 0.111                  |
| C5          | 0.157                  |
| C6          | 0.145                  |

Table 4.3 Zinc analysis of Commercial Oils.

From this data it is easy to calculate the molar percentage of ZDDP in the commercial oils. Since each ZDDP molecule contains 1 Zn atom the molar percentages of Zn and ZDDP will be the same and will be the weight % of Zn divided by the atomic weight of Zn. Table 4.4 shows the molar concentration of ZDDP in each oil.

| Oil         | Molar % Zn |
|-------------|------------|
| B2 + 0.2% C | 0.0003     |
| B2 + 2% C   | 0.003      |
| C1          | 0.0018     |
| C2          | 0.0024     |
| C3          | 0.0019     |
| C4          | 0.0017     |
| C5          | 0.0024     |
| C6          | 0.0022     |

Table 4.4 Molar percentage of ZDDP in Commercial Oils

Unfortunately Commercial users tend to quote ZDDP concentration in weight %. It is not possible to convert table 4.4 to such units without knowledge of the molecular weight of the ZDDPs and their structure. This was not available.

However the molar percentage is in fact a more relevant value to lubricant performance since it provides a direct comparison of the percentages of S, Zn and P in different lubricants.

The zinc analysis has however shown two points :

a) The 'control' base oils have molar percentages of zinc, in the correct ratio, i.e. 1 : 10. This implies that the zinc analysis has been reliable.

b) Unfortunately no direct correlation between polishing percentage and molar percentage ZDDP was detected. This may be due to the presence of other additives in the commercial oils (e.g. detergents, dispersants, V.I. Improvers and so on) and also variations in ZDDP structure i.e. different alkyl groups.

It was decided that in order to estimate the importance of ZDDP concentration in bore polishing a controlled set of lubricants would be used, with only a ZDDP additive present. This study is described in the next chapter.

#### 4.4 Discussion

This chapter has described a sequence of tests with a range of commercial lubricants of known polishing percentage defined by the Ford Tornado test. There is clearly a great deal of similarity between the tests conducted in the H.F.R. and Ford Tornado. In particular -

1) In terms of surface appearance of heavily polished and lightly polished liners. In order

to investigate the surface roughness of each liner a Talysurf profile was made for each oil at the same temperature. These results are summarised in the table below :

| Oil | Ford Tornado % | Visual condition of H.F.R. liners | C.L.A. of H.F.R. liners |
|-----|----------------|-----------------------------------|-------------------------|
| C1  | 17             | Light polish                      | 0.58 $\mu\text{m}$      |
| C2  | 45             | Heavy polish                      | 0.2 $\mu\text{m}$       |
| C3  | 15             | Light polish                      | 0.53 $\mu\text{m}$      |
| C4  | 55             | Heavy polish                      | 0.18 $\mu\text{m}$      |
| C5  | 20             | Light polish                      | 0.50 $\mu\text{m}$      |
| C6  | 15             | Light polish                      | 0.52 $\mu\text{m}$      |

Table 4.5 Comparison of commercial oils for 250°C test

There is clear correlation between H.F.R. values of C.L.A. and Ford Tornado polishing percentages. McGeehan ( 14 ) states that a heavily polished surface has a C.L.A. value of less than 5 $\mu\text{in}$  (approximately 0.12  $\mu\text{m}$ ) and for the heavily polished H.F.R. liners C2 and C4, the C.L.A. results approach this value.

2) Surface and subsurface deformation. Both the Ford Tornado and the H.F.R. identified subsurface deformation with heavily polished liners, although this was more marked in the Ford Tornado tests. With lightly polished liners, neither test identified extensive subsurface deformation.

- 3) The presence of sulphur in cavities on heavily polished surfaces, but nowhere else.

In order to attempt to characterise a heavily polished surface the range of techniques described in this chapter were conducted. The results of these tests indicate that a heavily polished surface is;

- a) Not produced by a 'filling-in' process. This is indicated from the micro-sectioning.
- b) Associated with high stress rather than low stress. This is indicated by subsurface deformation for heavily polished liners.
- c) Not associated with the formation of a glaze or a white layer.
- d) Associated with sulphur traces in cavities, indicated by m.p.a.
- e) Evidenced by delamination wear particles, some corrosive pitting and also scratching in the sliding direction, possibly indicative of abrasive wear.

The effect of temperature on the severity of polishing seems clear. There is evidence from the surface visual S.E.M. study, that higher temperature promote greater polishing. At higher temperatures the

appearance of possible corrosive pits is also indicated. This may suggest that removal of surface layers is by corrosive wear. The result of drip feeding the oil appeared to be a lessening of wear damage although the correlation between H.F.R. and Ford Tornado tests still existed. The reasons for this were not clear, although high contact voltage traces could indicate the formation of a thick film on top of the existing antiwear or E.P. film, thereby reducing the severity of wear. However the reason why oils C2 and C4 (the heavily polishing oils) afforded less protection to the surface is unclear. However once the smoothening of the surfaces has begun it is likely to be accelerated by the occurrence of high temperatures, high stress and the three wear processes, delamination, corrosive and abrasive wear.

The literature gives very little information on microanalysis of bore polished liners. Ayel et al ( 62 ) conducted a microanalysis on liners from a Petter AVB (turbocharged) diesel engine and also observed the association of sulphur in heavily polished liner cavities. They related this to the quality of the combustion and to the fuel content. There is no evidence for the filling-in process described by Sreenath and Ramon ( 35 ) or the formation of a glaze described by Montgomery ( 18 ) amongst others, or of a white layer. There is evidence to support the view that abrasive wear is associated with bore polishing, as mentioned by Ayel et al ( 39 ). However these



investigations rule out corrosive wear and plastic deformation, whilst the study conducted suggests that these processes do occur in bore polishing. Finally, the literature suggests that piston ring interaction is significant in bore polishing and this study would support this view. Clearly the effect of the lubricant is of great importance also.

The study conducted in this chapter suggests a number of important points which may help our understanding of the bore polishing process. Whilst there are clearly a number of mechanisms by which heavy polishing may occur, the mechanism suggested below has not been reported in the literature. There is considerable information to link sulphur deposits on the surface with E.P. activity when ZDDP is the oil additive. Furthermore, the formation of an E.P. film is greatly affected by 1) Concentration, 2) Temperature and finally 3) Severe stress. In the heavy polishing process it is clear that a deformed smooth surface is produced which would enhance the formation of an iron sulphide film due to 2) and 3). The reaction rate would be influenced by these 3 factors although in this current study 1) has not been considered, since the ZDDP concentrations were fixed by the manufacturers and were of similar value. The formation of smooth surfaces could greatly increase the interfacial temperature and contribute to a rapidly formed surface film. The removal of this reacted iron sulphide film could accelerate removal of surface layers by 1) Corrosive

wear, 2) Abrasive wear due to corrosion products and 3) Delamination wear caused by high cyclic stresses. Once this process has been initiated it could accelerate when corrosive wear becomes significant. The reasons for the initiation of this process are not clear from the tests conducted.

In order to attempt a correlation between ZDDP concentration and bore polishing percentage, the zinc analysis was conducted. Unfortunately no relationship was detected and it was decided to conduct a controlled set of experiments with known ZDDP concentration and no other additives present. This is described in the next chapter.

Finally, the effect of bore polishing on engine efficiency is discussed. It is clear that the light polishing oils (C1, C3, C5 and C6) produce a liner surface which is not heavily polished, with the honing pattern still identifiable. Under these conditions it is likely that oil retention will be provided and blow-by will not occur. However for oils C2 and C4 the honing pattern is removed and the liners have heavy polish. Under these circumstances it is likely that bore polishing will have a serious effect upon the efficiency of the engine, with blow-by occurring. From these comments it is suggested that bore polishing percentages of 45% or over represent a serious service problem with loss of engine efficiency and probable chances of scuffing whilst percentages of 20% or lower

do not present the same threat to engine efficiency.

#### 4.5 Conclusions

A number of conclusions can be drawn from the experiments conducted in this chapter.

1) There is close similarity between the bore polishing tests conducted in the Ford Tornado engine and the H.F.R. device. This similarity has three forms;

a) Appearance of liner surfaces, by S.E.M. and surface roughness.

b) Surface and subsurface deformation of liner specimens.

c) The presence of sulphur in polished liner cavities, but nowhere else on the liners.

2) There is evidence of plastic deformation on the worn surfaces of test liners. In particular, greater deformation appears to be associated with more highly polished surfaces.

3) A limited amount of evidence for abrasive wear has been found. In particular this seemed more relevant to smooth surfaces rather than rough ones.

4) A number of sheet-like particles were observed on the heavily polished surfaces, similar to delamination wear particles described by Suh. The existence of these particles was confirmed by ferrography in heavy polishing oils.

5) The presence of sulphur associated with polished liner cavities could indicate that polishing is associated with E.P. action rather than antiwear action. In particular the sulphur seems more associated to highly stressed areas and this could be indicative of the formation of iron sulphide films on heavily polished surfaces. The removal of these films by the piston ring could suggest that polishing is partly a corrosive wear mechanism.

6) An attempt to ally the performance of each oil to ZDDP concentration by zinc analysis was unsuccessful, although no conclusions could be drawn from this. It was decided to conduct a controlled series of tests with varying ZDDP concentration. (Next chapter).

7) The effect of temperature on polishing appears to be an increasing of plastic deformation and also polishing severity.

8) The effect of inclining the apparatus and drip feeding was a lessening of surface deformation and polishing; this could be due to the formation of an absorbed thick film on existing surface films, although this was not clear.

9) Bore polishing percentages greater than 45% appear a serious problem for engine serviceability and efficiency, whilst percentages less than 20% do not appear to present a significant danger to engine serviceability.

C H A P T E R 5

Bore polishing Tests with base stock and ZDDP

Additive

## CHAPTER 5

### Bore polishing Tests with base stock and ZDDP additive

#### 5.1 Introduction

In the previous chapter it was shown that a good correlation between H.F.R. tests and practice was obtained. In an attempt to gain further insight of possible mechanisms of bore polishing the ZDDP concentration of the lubricating oils was singled out for further investigation. This chapter describes H.F.R. tests on 7 oils consisting of a base stock B2, with varying concentrations of a commercial antiwear additive, C. Tables 5.1 and 5.2 give suppliers specification

The experiments had the following aims :

- 1) To determine visually, by S.E.M., the effect of ZDDP concentration on the severity of polishing on H.F.R. liners.
- 2) To prepare a number of micro-sections in order to investigate microstructural changes associated with heavy polishing, and also to determine whether a glaze, white layer or any other form of coating was associated with heavy polishing by ZDDPs.
- 3) To conduct a microprobe analysis of H.F.R. wear scars to determine their chemistry.
- 4) To conduct ferrography on run H.F.R. lubricants for evidence of wear debris.
- 5) To incline the H.F.R. apparatus and drip feed each lubricant onto the liner specimens. The analyses conducted for the immersed tests were to be

|                                    |       |
|------------------------------------|-------|
| Colour N P A                       | 2     |
| Density at 15°C Kg m <sup>-3</sup> | 0.884 |
| Viscosity in centistokes           |       |
| at 37.7°C                          | 82.34 |
| 50°C                               | 46.00 |
| 100°C                              | 9.50  |
| Viscosity Index                    | 101   |
| Pour point, °C                     | -9    |
| Flash point, °C                    | 290   |
| Ash content, %                     | 0.00  |

TABLE 5.1 Data on base stock B2

|                                   |                                |
|-----------------------------------|--------------------------------|
| Type                              | Dialkyl                        |
| Alcohol                           | Primary                        |
| Alkyl                             | 50% Isopropyl,<br>50% Isobutyl |
| Thermal decomposition temperature | 205°C                          |
| Phosphorous content               | 9.5%                           |
| Sulphur content                   | 20.0%                          |
| Zinc content                      | 10.6%                          |

TABLE 5.2 Data on ZDDP additive C. (Lubrizol 1395)



conducted for drip feed tests and the two sets of results compared.

6) To use the results of the various techniques in order to:

a) Gain insight into the effect of ZDDP concentration on bore polishing.

b) Gain further understanding of the mechanisms of bore polishing.

## 5.2 Test programme

As in the previous chapter, the tests can be split into two sections. (See sections 5.2.3 and 5.2.4).

### 5.2.1 Formulation of base oils

A 40 c.c. specimen bottle was cleaned with toluene and acetone and then weighed. Base oil B2 was then added and the specimen bottle re-weighed and the mass of base oil deduced. The additive C was then carefully added until the correct weight concentration had been achieved. The bottle was then sealed, shaken and allowed to stand.

### 5.2.2 Preliminary tests

A series of tests were conducted initially to determine the range of concentrations to be investigated. The concentrations first chosen were 0.25%, 0.5%, 0.75%, 1%, 1.5% and 2% (w/w).

From these preliminary tests it was observed that the 1.5% concentration did not differ significantly from the 2.0% concentration and so was eliminated. For lower concentrations 0.1% and 0.4% were also investigated and it was noticed that, whilst 0.1% and 0.25% were very similar, 0.4% was completely different from either 0.25% or 0.5%. From these initial tests it was decided that the concentrations most worthy of further investigation were 0.25%, 0.4%, 0.5%, 0.75%, 1% and 2%. The base stock itself was also to be tested.

### 5.2.3 Immersed contact tests

These tests were conducted in the manner described on Page (93). Again the specimens were cleaned before the S.E.M. analysis. The table below summarises the tests conducted in this section.

| OIL         | TEST TEMPERATURES (TEST TIMES)          |
|-------------|---|
| B2          | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |
| B2 + 0.25%C | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |
| B2 + 0.4%C  | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |
| B2 + 0.5%C  | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |
| B2 + 0.75%C | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |
| B2 + 1.0%C  | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |
| B2 + 2.0%C  | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |

TABLE 5.3 Programme for immersed contact tests on base stock oils

#### 5.2.4 Drip feed tests

These tests were conducted by the same method as described in Section 4.2.2 on Page 112. The table below summarises the tests conducted in this section:-

| OIL         | TEST TEMPERATURES (TEST TIMES)          |
|-------------|---|
| B2          | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |
| B2 + 0.25%C | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |
| B2 + 0.4%C  | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |
| B2 + 0.5%C  | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |
| B2 + 0.75%C | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |
| B2 + 1.0%C  | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |
| B2 + 2.0%C  | 200°C (2hrs), 250°C (2hrs), 300°C (1hr) |

TABLE 5.4 Programme for drip feed tests on base stock oils

### 5.3 Results

#### 5.3.1 Immersed contact tests

As in the last chapter the results take two forms.

##### 5.3.1.1 Pen recorder

For the 200°C tests it can be seen that a thick boundary film has been accomplished in all cases. With the exception of the base stock the oil films are very stable. The friction coefficient plots indicate that the 0.25%, 0.4%, 0.5% and 1% oils are very stable and lower than the other oils.

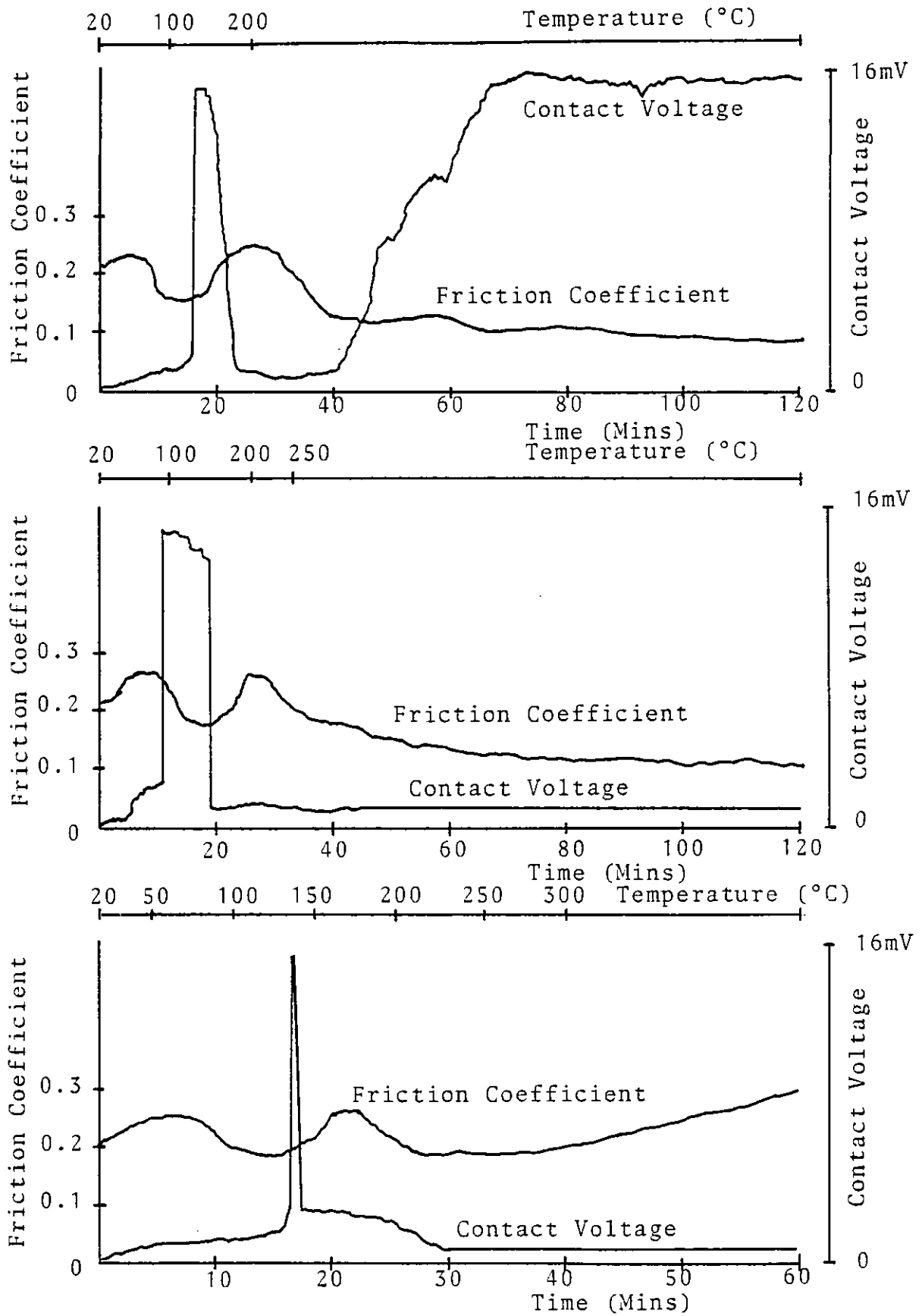


FIGURE 5.1 B2 at 200°C, 250°C, 300°C (immersed)

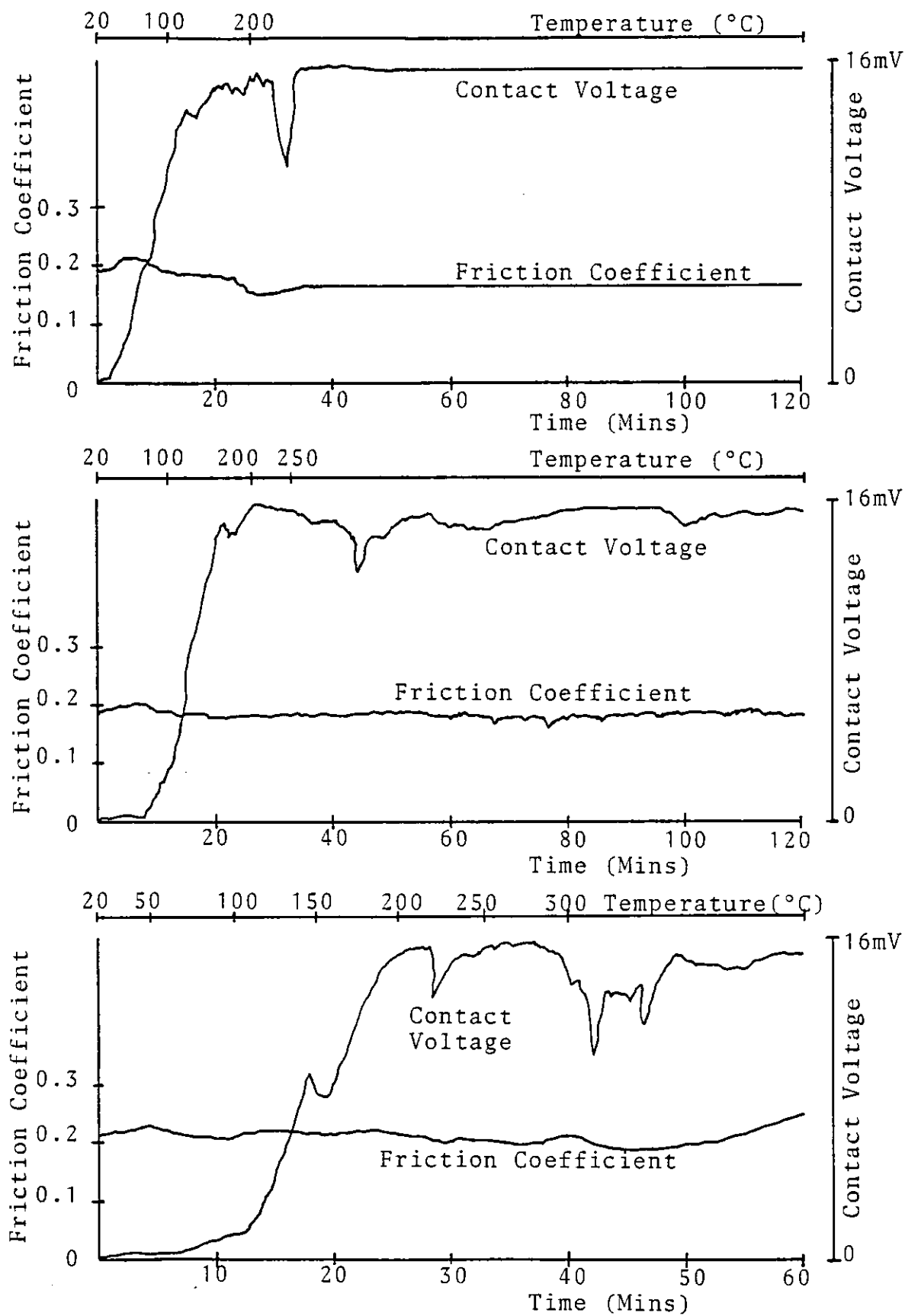


FIGURE 5.2 B2 + 0.25%C(w/w) at 200°C, 250°C, 300°C (immersed)

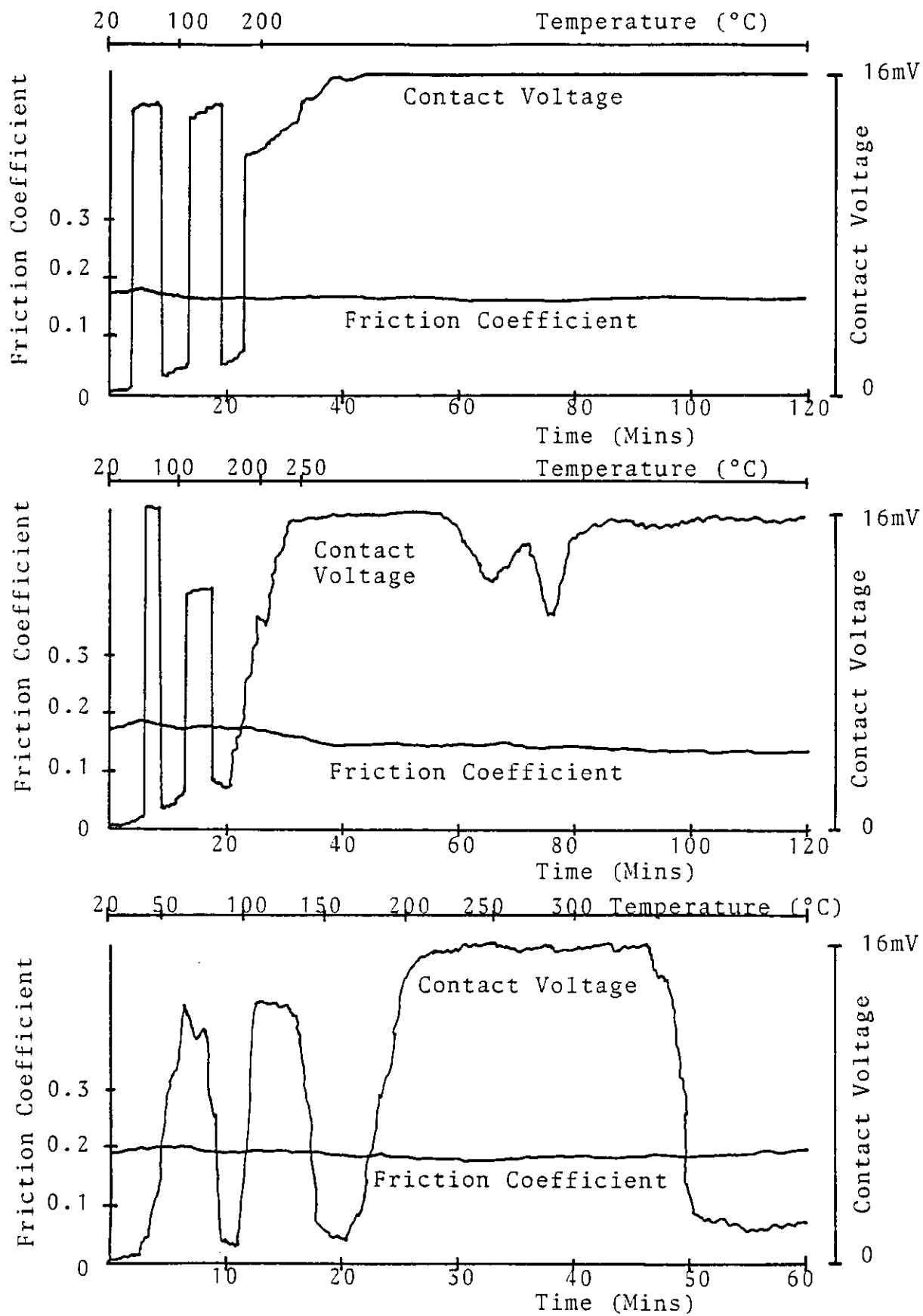


FIGURE 5.3 B2 + 0.4%C(w/w) at 200°C, 250°C, 300°C (immersed)

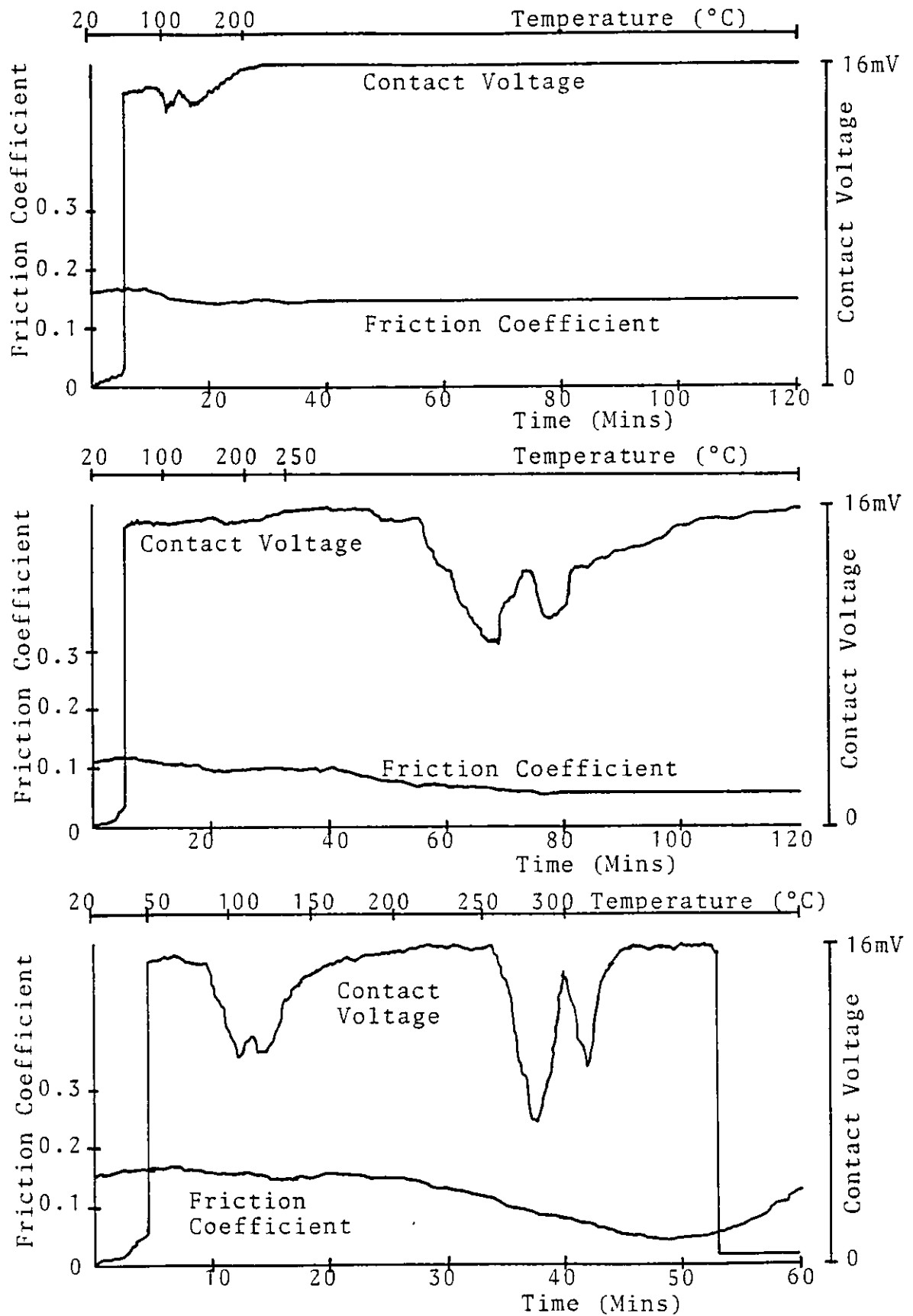


FIGURE 5.4 B2 + 0.5%C(w/w) at 200°C, 250°C, 300°C (immersed)

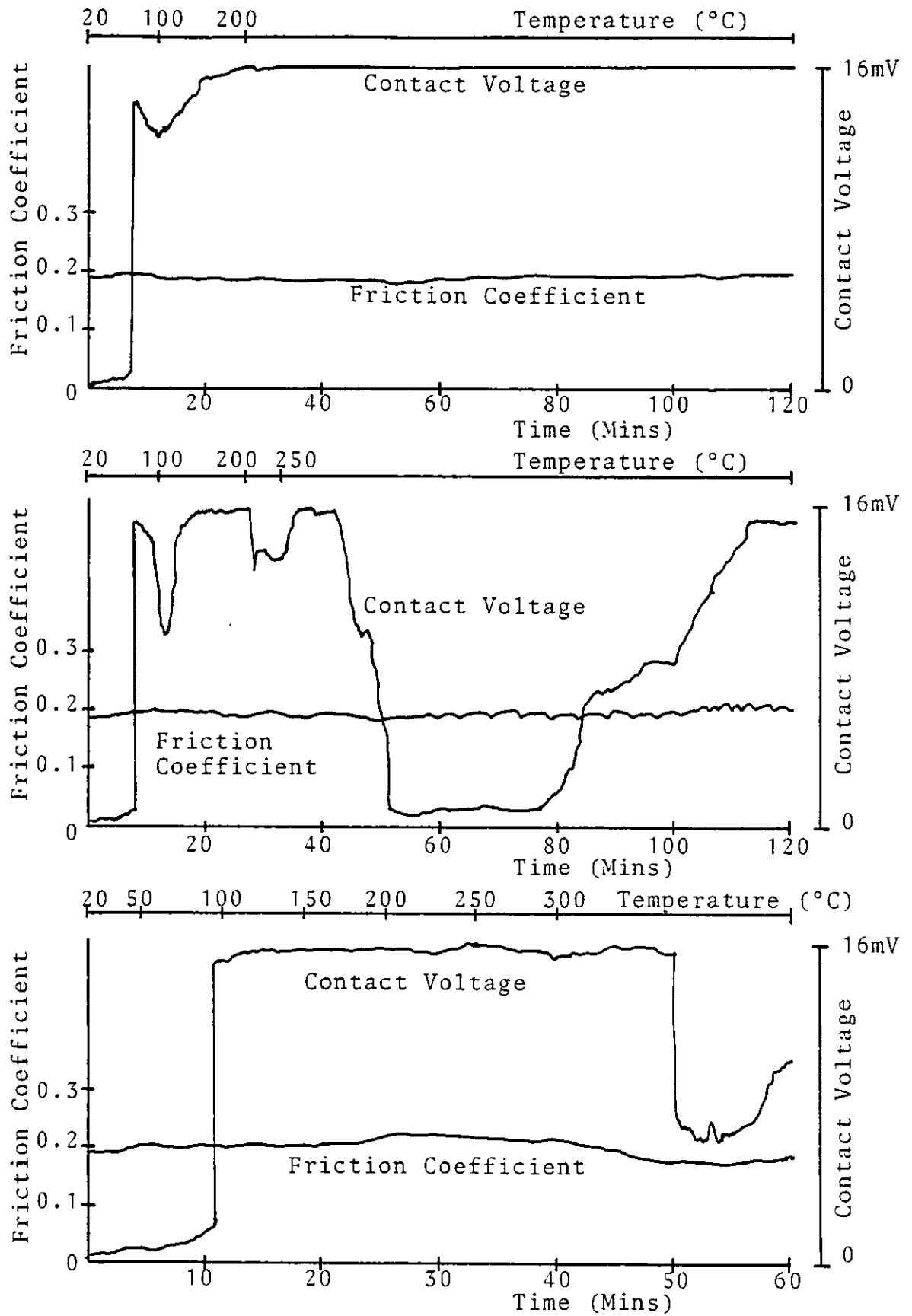


FIGURE 5.5 B2 + 0.75%C(w/w) at 200°C, 250°C, 300°C (immersed)



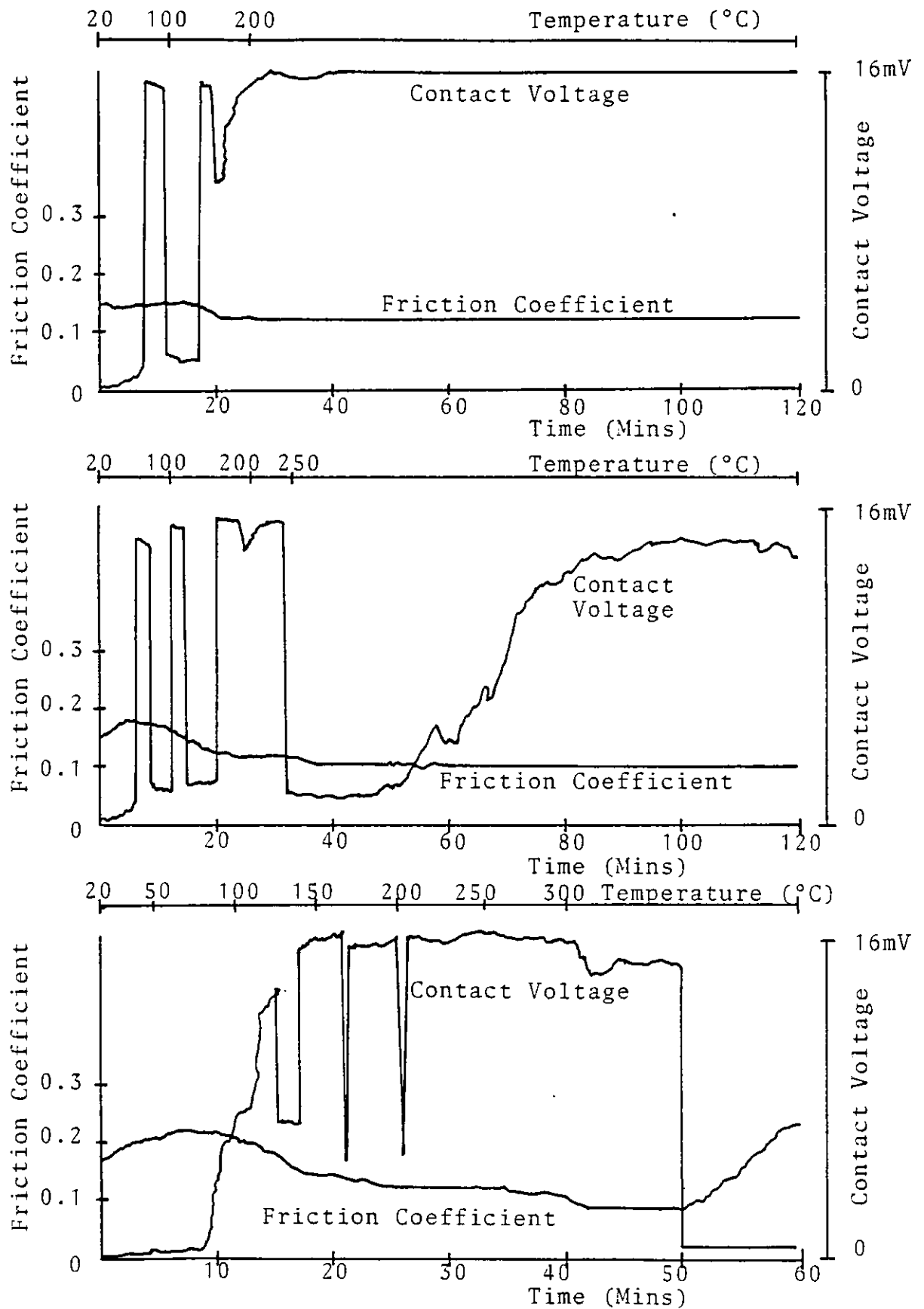


FIGURE 5.6 B2 + 1%C(w/w) at 200°C, 250°C, 300°C (immersed)

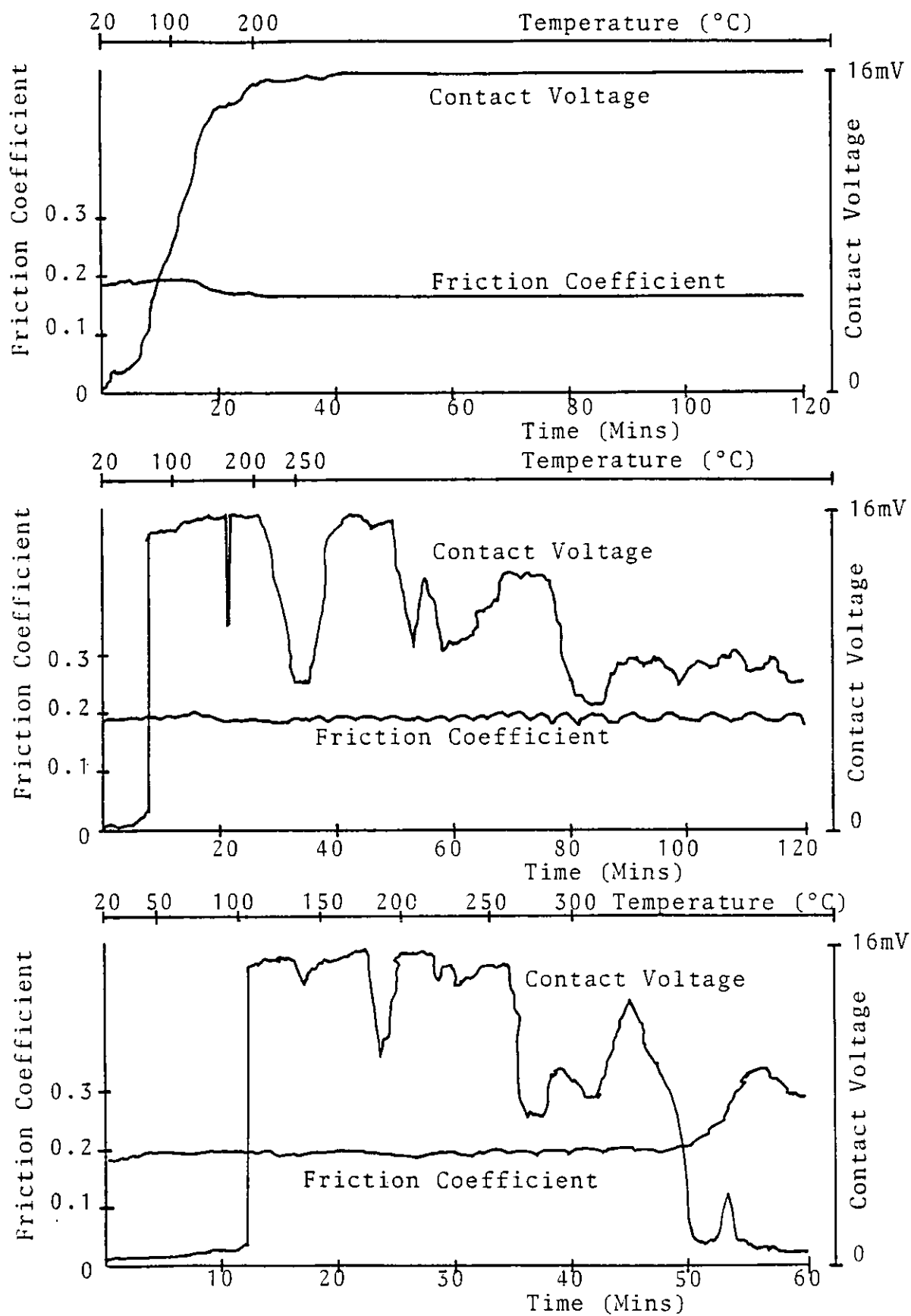


FIGURE 5.7 B2 + 2%C(w/w) at 200°C, 250°C, 300°C (immersed)

For the 250°C tests the 0.25%, 0.4% and 0.5% concentrations indicate a thick boundary oil film for most of the test whilst the other concentrations have less stable oil films. This is also largely true for the friction coefficient trace which is unstable for the 0.75% and 2% concentrations. Once again the 0.4%, 0.5% and 1% concentrations indicate a lower friction coefficient than the other oils.

For the 300°C tests all the oils exhibit unstable oil films which are maintained for varying periods of time. The 0.5% and 0.25% concentrations have oil films established for the majority of the test and there is a tendency for the oil film to become less stable with increased concentration. The friction coefficient for each test, with the exception of 0.4% concentration, tends to increase towards the end of the test. The 0.5% concentration has the lowest friction coefficient of any test conducted in this section although it is not stable.

### Deductions

- 1) There is a general trend towards less stable oil films and less stable friction coefficients with increasing concentration. This tendency appears to accelerate at concentrations above 0.75%.

2) The lowest friction coefficient is indicated for the 0.5% concentration oil. Both the 0.4% and 0.5% concentration oils appear more stable than the other oils.

3) The additive has greatly improved the oil film thickness when compared to the base stock and there is evidence of a stabilised friction coefficient at higher temperatures.

4) It is not possible to deduce any information on the likelihood of bore polishing severity for each oil, although it is probable that 0.4% and 0.5% concentrations would be better inhibitors of bore polishing than the other oils since they have low friction coefficients which are mostly stable.

#### 5.3.1.2 Visual S.E.M.

The photographs on pages 193 to 195 represent the visual examination carried out on the liner surfaces from the immersed tests on the base stock oils. The following points emerged from this study :

1) There was a clear difference in surface smoothness with different additive concentration. The 0.4% concentration appeared to give the least polishing whilst higher concentrations (above 0.75%) and lower concentrations (particularly B2

alone) gave the most smooth surfaces. This is illustrated in figures 5.8 to 5.10 .

2) Increasing the temperature did not have such a marked effect on polishing as in the previous chapter with commercial oils. There was, however, a slight tendency for severity of polishing to become greater at higher temperatures and in no cases did the apparent smoothening of the surface become less at higher temperatures. This is illustrated in figures 5.8 and 5.11, where the higher temperature test ( $250^{\circ}\text{C}$ ) exhibits a slightly higher amount of surface smoothening than the lower temperature test ( $200^{\circ}\text{C}$ ). Once again probable corrosive pitting was observed in a few cases, but only at high temperatures and high concentrations as shown in figure 5.10.

3) Figures 5.8 and 5.11 show evidence of plastic deformation around the honing lines. As with commercial oil tests in the previous chapter it was not possible using visual S.E.M. of the liner surfaces to determine whether plastic deformation or 'filling-in' of the honing marks has occurred on heavily polished surfaces. (As in figure 5.9 ). The liners were sectioned to investigate changes in their microstructure. This is described in the next section.

4) Figure 5.13 is a high magnification view of a



Figure 5.8 S.E.M. View of Liner with B2+0.4%C<sup>(w/w)</sup> at 250°C (immersed). (200x)

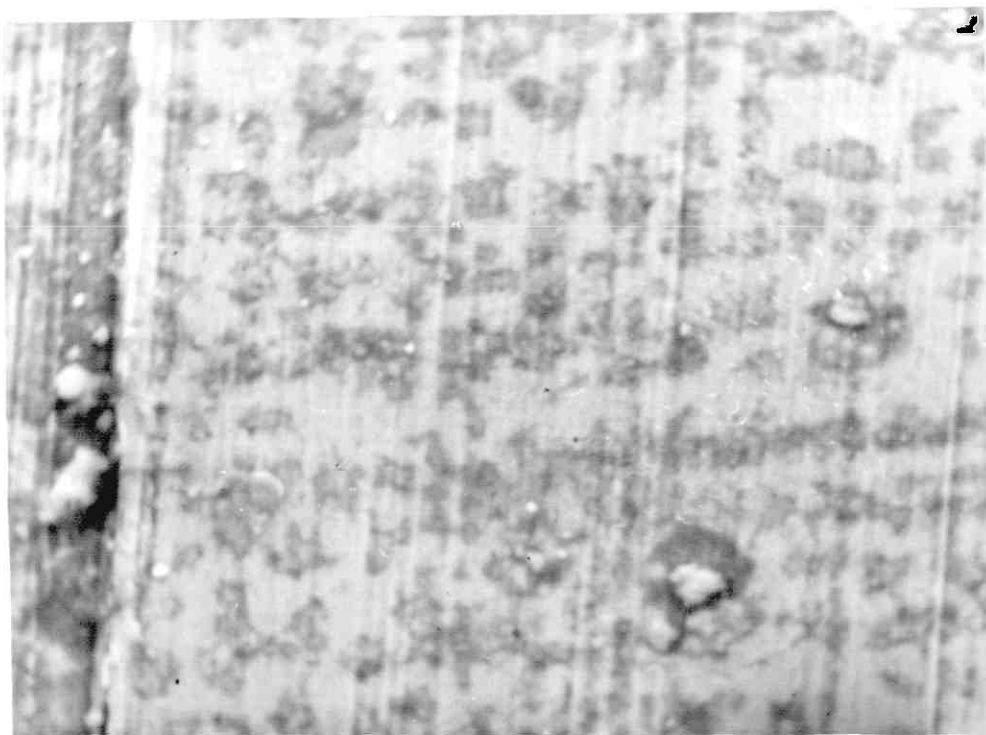


Figure 5.9 S.E.M. View of Liner with B2 at 250°C (immersed). (200x)

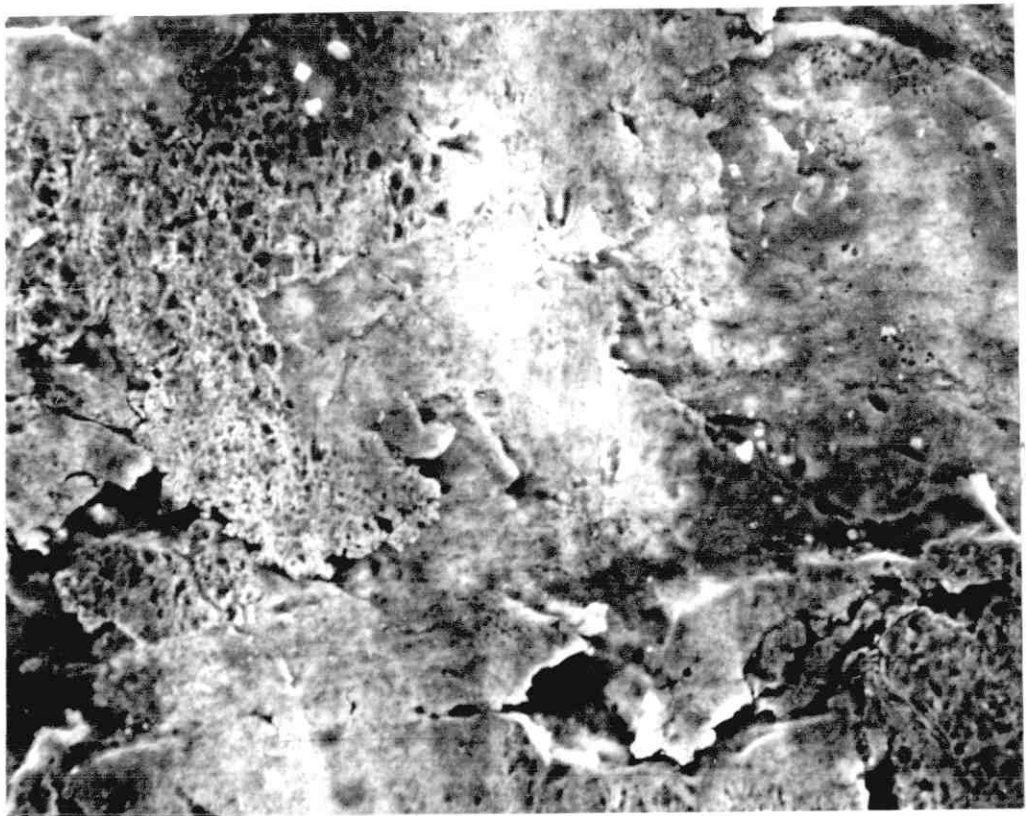


Figure 5.10 S.E.M. View of Liner with B2+2%C(<sup>w</sup>/w) at 250°C  
(immersed). (200x)



Figure 5.11 S.E.M. View of Liner with B2+0.4%C(<sup>w</sup>/w) at 200°C  
(immersed). (200x)

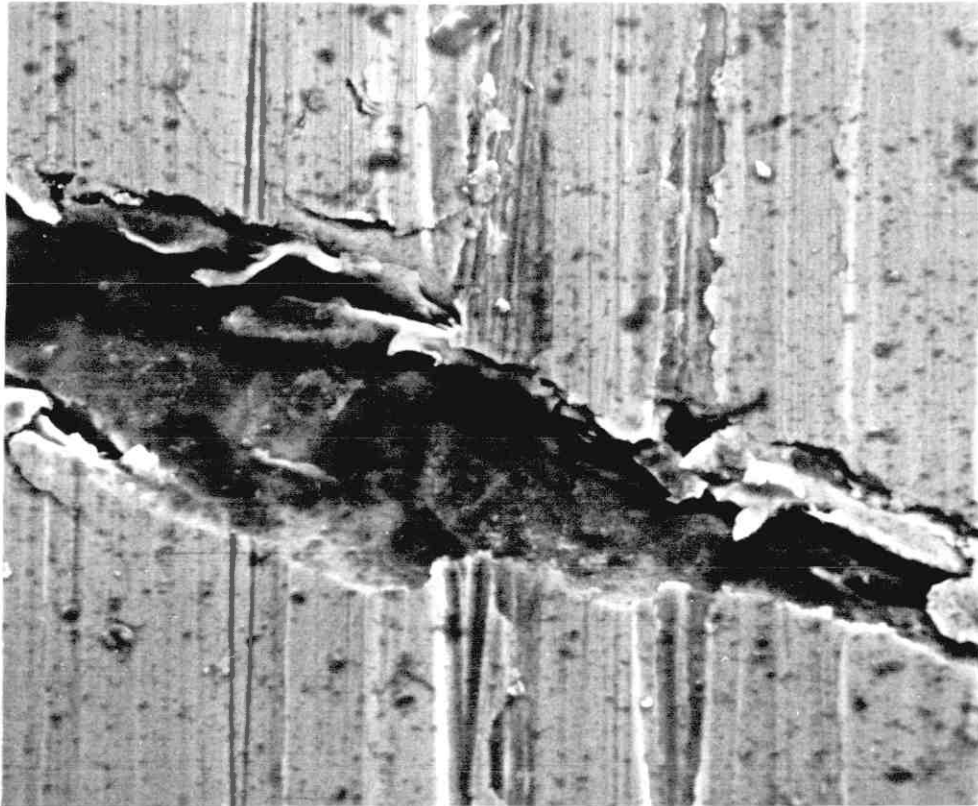


Figure 5.12 S.E.M. View of Liner with B2+0.75%C(<sup>w</sup>/w) at 200°C (immersed). (1000x)

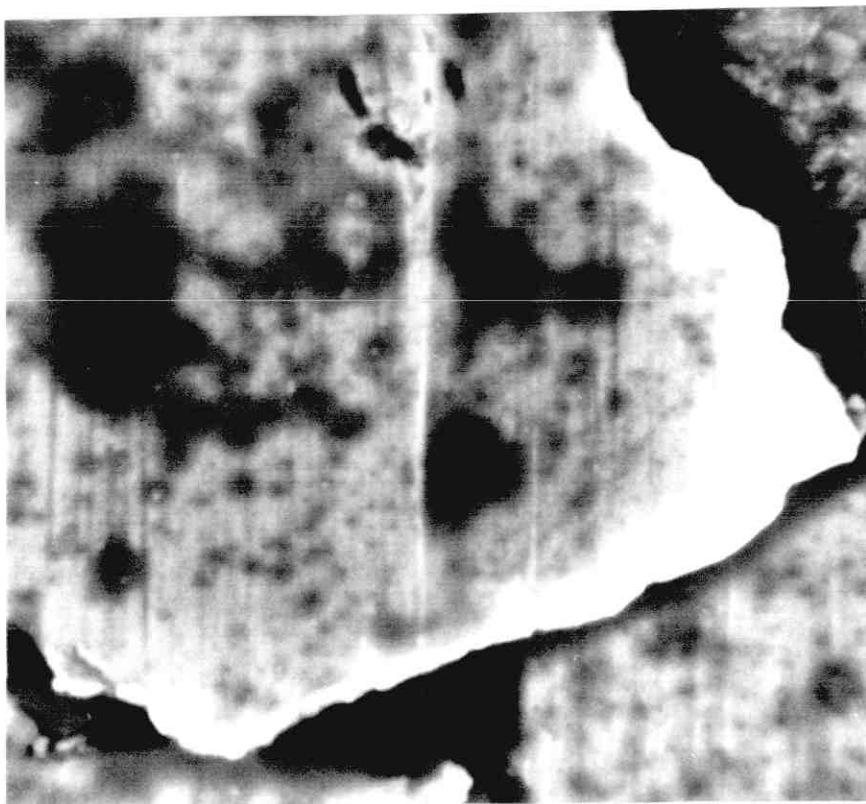


Figure 5.13 S.E.M. View of Liner with B2 at 300°C (immersed). (5000x)



probable delamination wear particle in the process of leaving the surface. Again these were only found on heavily polished surfaces. Ferrography was again conducted to confirm the presence of delamination particles (see Section 5.3.2.5).

5) On about 50% of medium and heavily polished liners continuous scratches were observed, representative of abrasive wear. Figure 5.12 is a good example of this, with the sliding direction being top to bottom. No such scratches were observed on lightly polished liners.

#### 5.3.1.3 Micro-sectioning

This section describes the micro-sectioning of H.F.R. liners from immersed base stock oil tests.

Figure 5.14 shows a taper section through the wear scar of a lightly polished liner. The cross hatching is clear (top of photograph) and the subsurface has very little evidence of cracking.

Figure 5.15 is a taper section through the boundary of wear scar (upper left-hand side) and unworn liner (upper right-hand side). There is considerably more evidence of cracking around the graphite flakes both on the surface and in the subsurface. The wear scar is also clearly pitted. The sliding direction in



Figure 5.14 Axial Taper Micro-section of Liner with  
B2+0.4%C (w/w) at 300°C. (200x)



Figure 5.15 Axial Taper Micro-section of Liner with  
B2+2%C (w/w) at 300°C. (200x)

these photographs is left to right.

These figures again indicate that the heavily polished surfaces (e.g. figure 5.15) are more highly stressed than the lightly polished surfaces (e.g. figure 5.14). Furthermore, there is no indication of a white layer, glaze or 'filling-in' process associated with either surface.

#### 5.3.1.4 Microprobe analysis

As in the previous chapter a microprobe analysis was conducted to compare the surface chemistry of H.F.R. test liners for polished and non-polished surfaces. Figure 5.16 shows the ratio of sulphur to silicon peak heights for each lubricant. Again it was observed that with the heavily polished liners the cavities revealed more sulphur than the lightly polished liner cavities. Figures 5.17 and 5.18 present evidence of this.

The analyses, revealing sulphur in highly polished liner cavities, could again suggest that surface smoothening is by E.P. action rather than antiwear action. This would correlate with the microstructural analysis which indicated that polished surfaces are highly stressed, thereby enhancing the likelihood of elemental sulphur formed on the surface. ( 3 )

The results from this section will be discussed

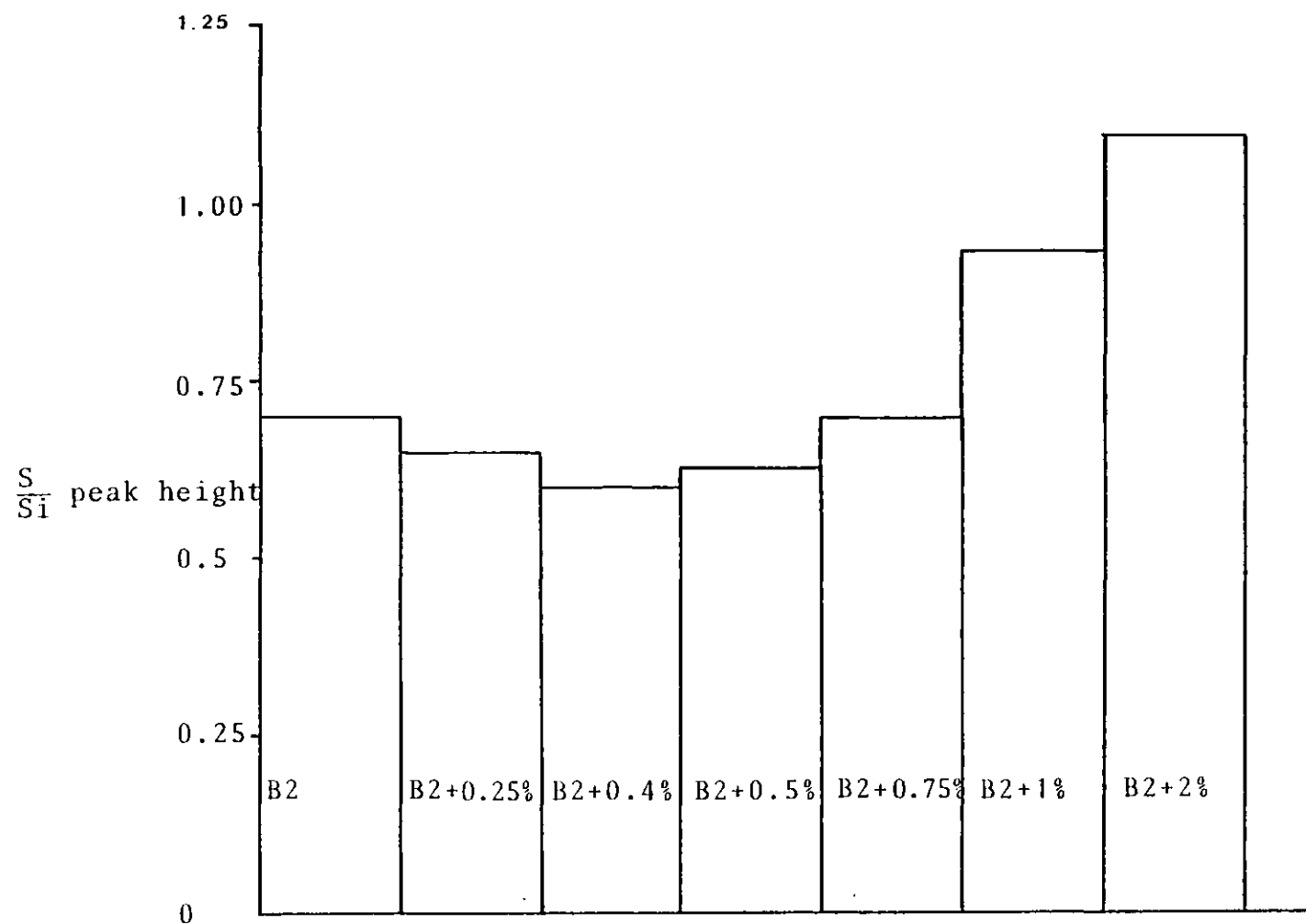


Figure 5.16 Ratio of  $\frac{S}{S_1}$  Peak Heights for Each Concentration

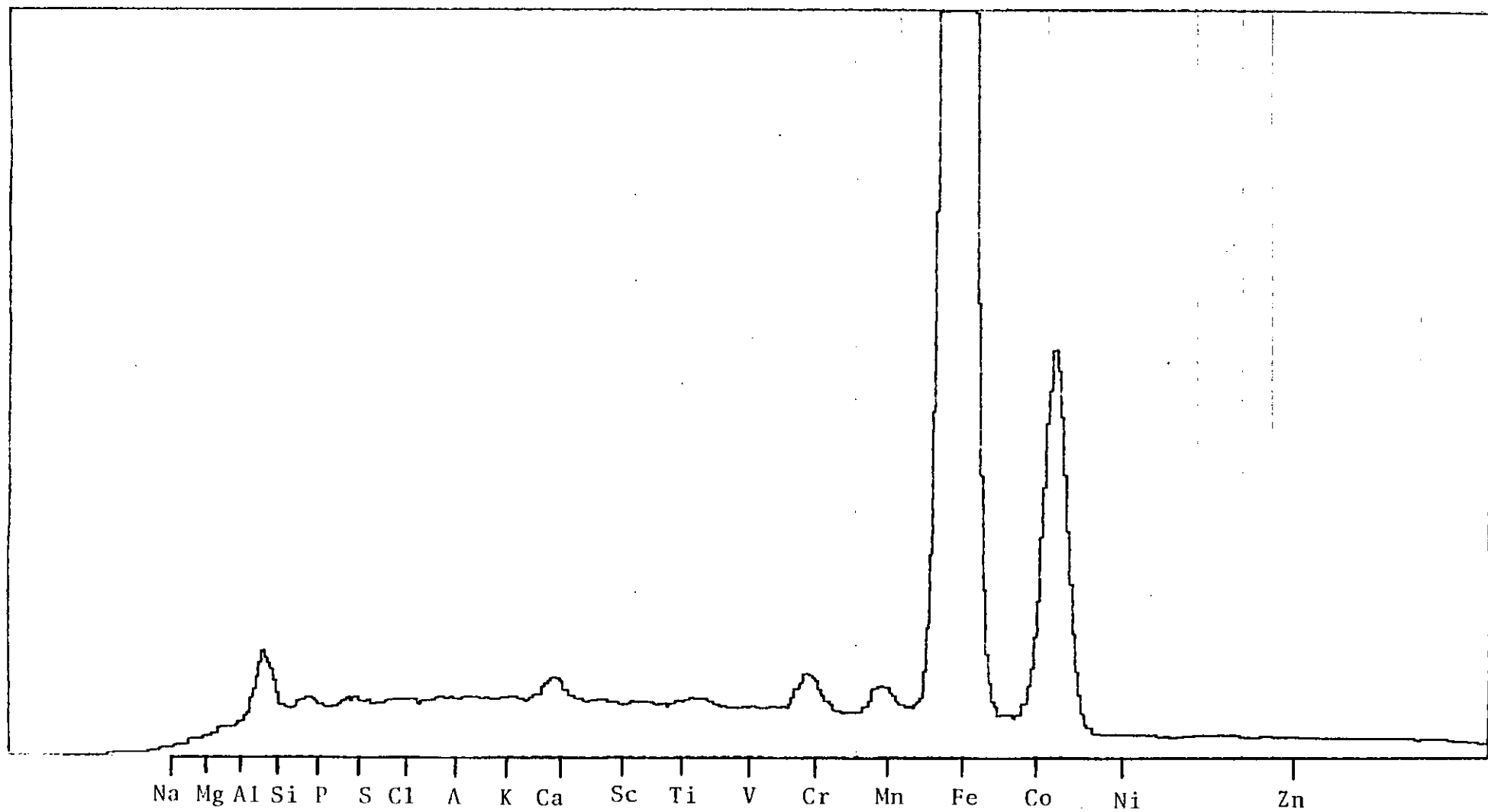


Figure 5.17 M.P.A. of Liner Cavity with B2 + 0.4%(w/w) at 300°C (spot)

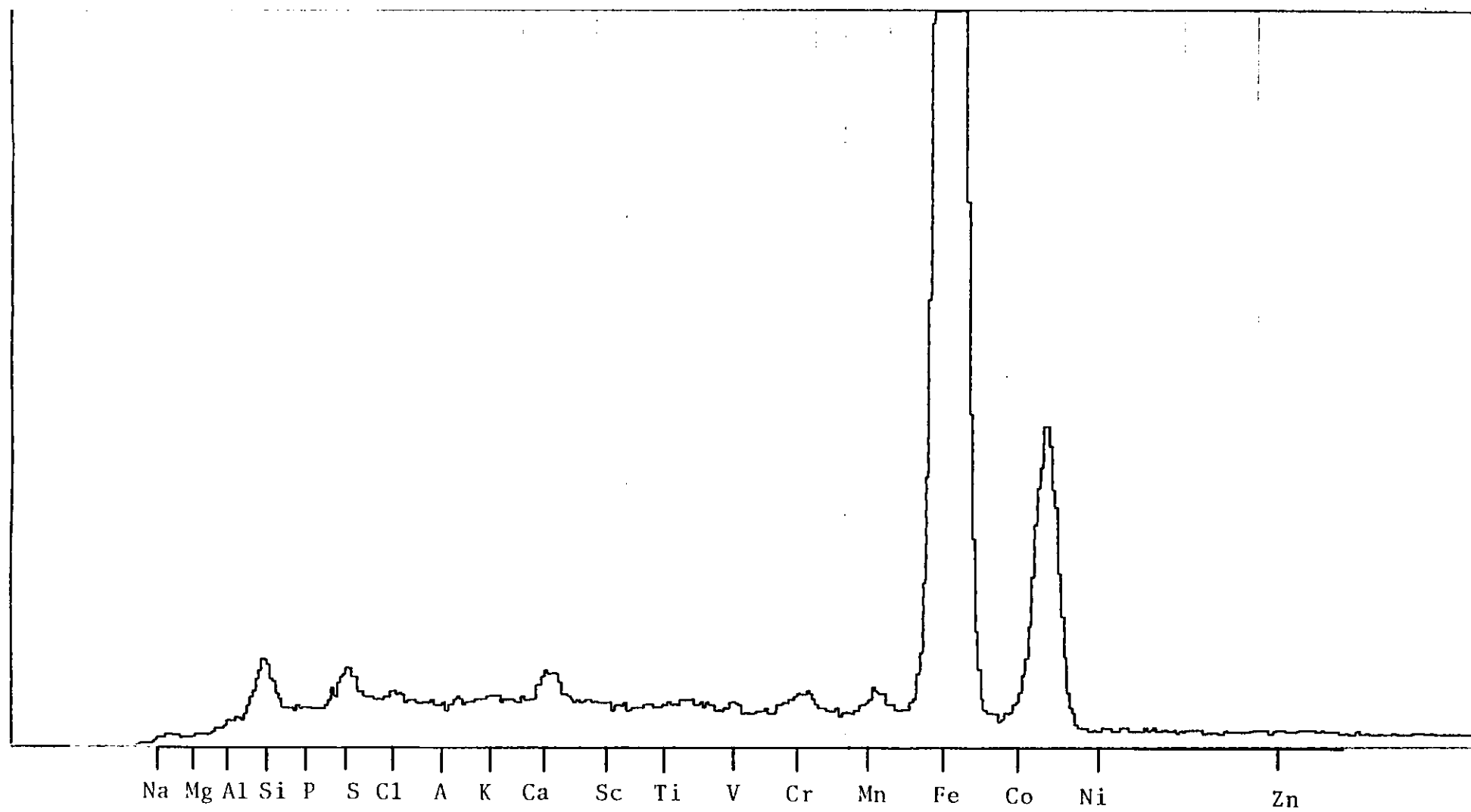


Figure 5.18 M.P.A. of Liner Cavity with B2 + 1%(w/w) at 300°C (spot)

in Section 5.4.

### 5.3.2 Drip feed tests

Again these results take five forms.

#### 5.3.2.1 Pen recorder

The 200°C tests indicate again that each oil establishes a thick boundary oil film which is attained more rapidly than that of the base stock. The 0.25% and 0.5% concentrations attained thick films almost immediately. Each oil up to and including 0.75% additive concentration exhibits a stable friction coefficient whilst the 1% and 2% concentrations show the 'saw tooth' profile observed in chapter 4.

The 250°C tests show very little variation from the 200°C test. Each oil again indicates a thick film for most of the test whilst the friction coefficient has become stable for nearly every oil. The 0.5% concentration indicates a 'saw tooth' profile for half the test.

The 300°C tests show the presence of a thick film for each oil other than the base oil. There is further evidence to suggest that for 0.75% concentration and higher concentrations the friction coefficient is less stable. This is indicated

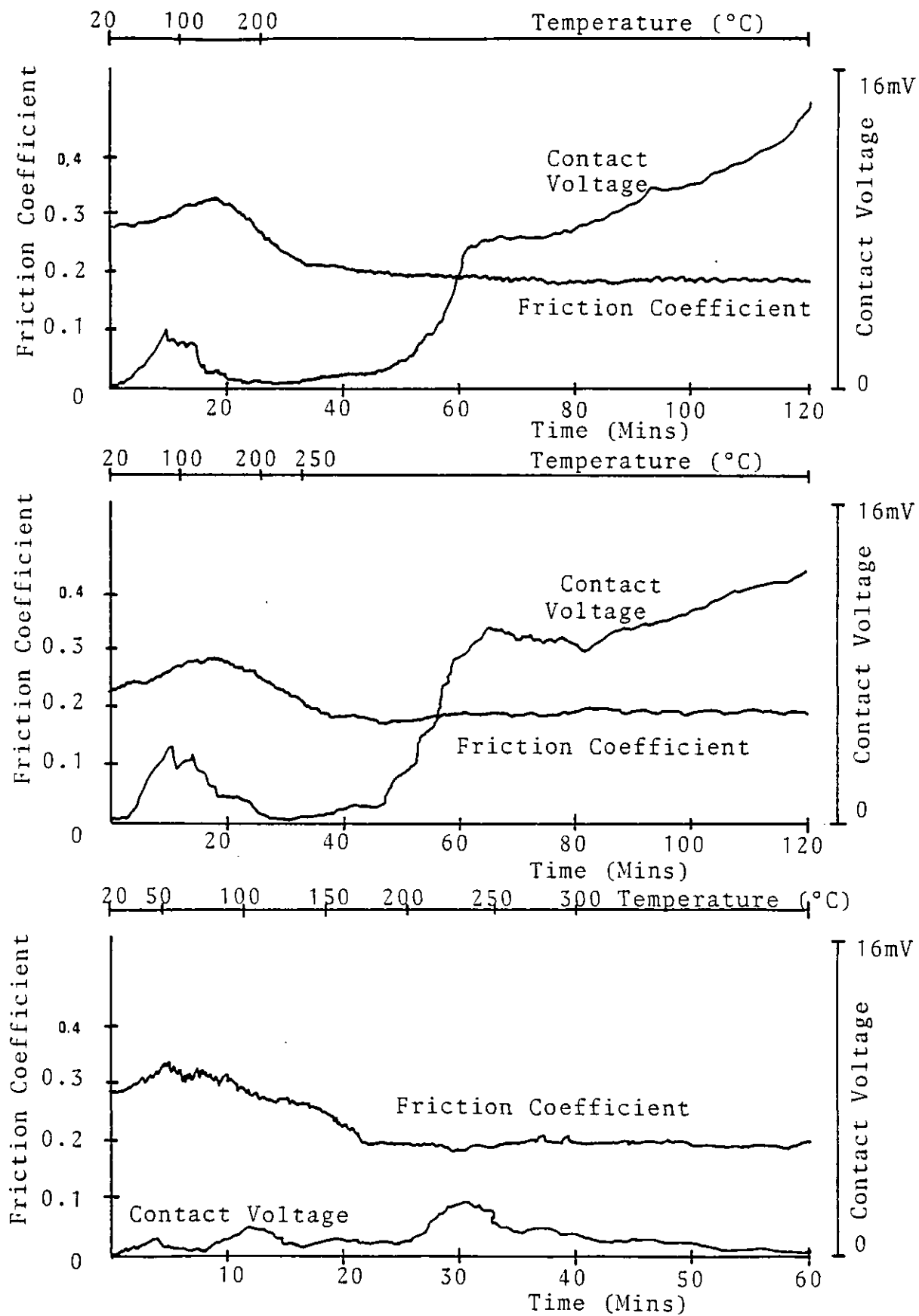


FIGURE 5.19 B2 at 200°C, 250°C, 300°C (drip feed)



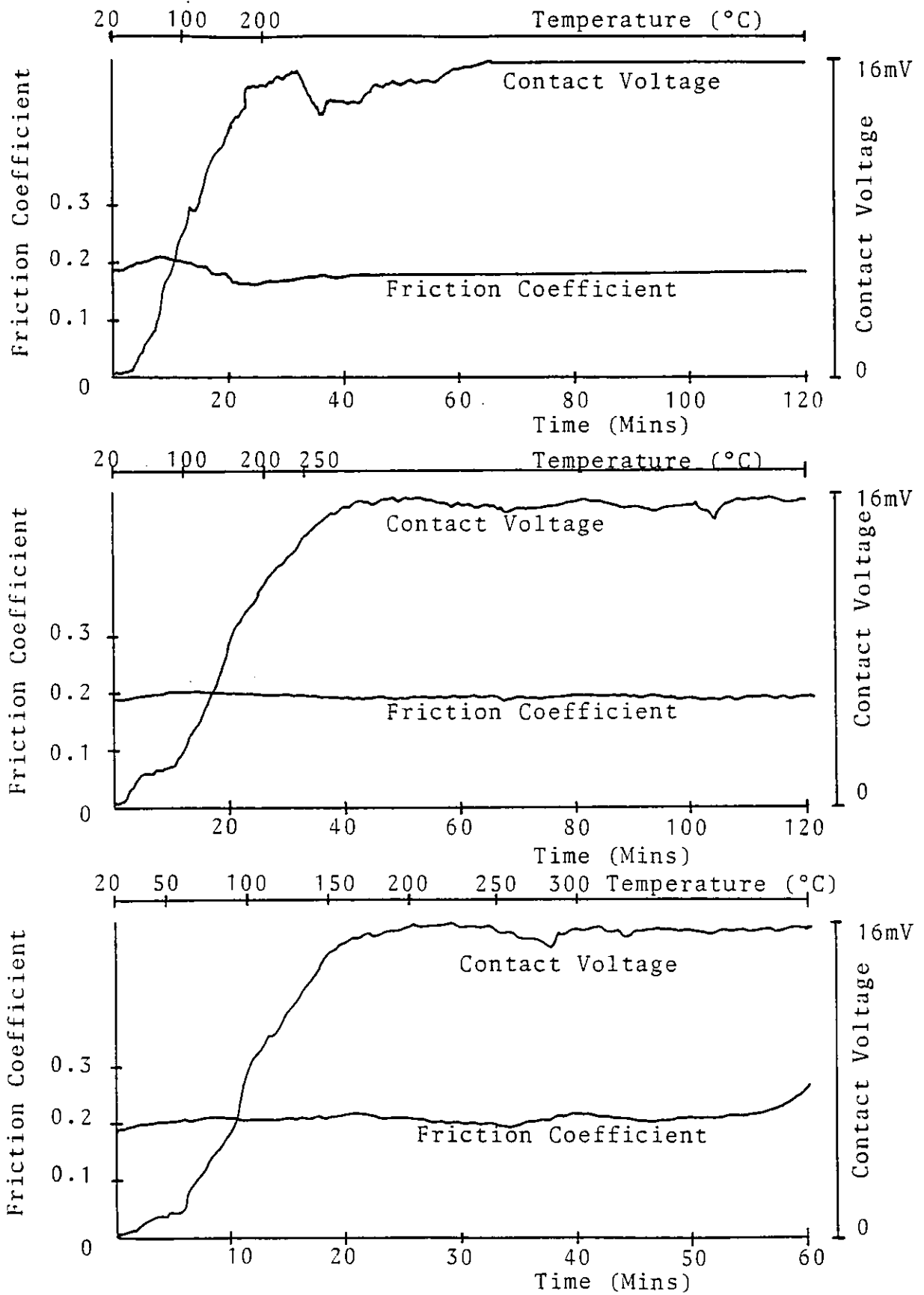


FIGURE 15.20 B2 + 0.25%C(w/w) at 200°C, 250°C, 300°C (drip feed)

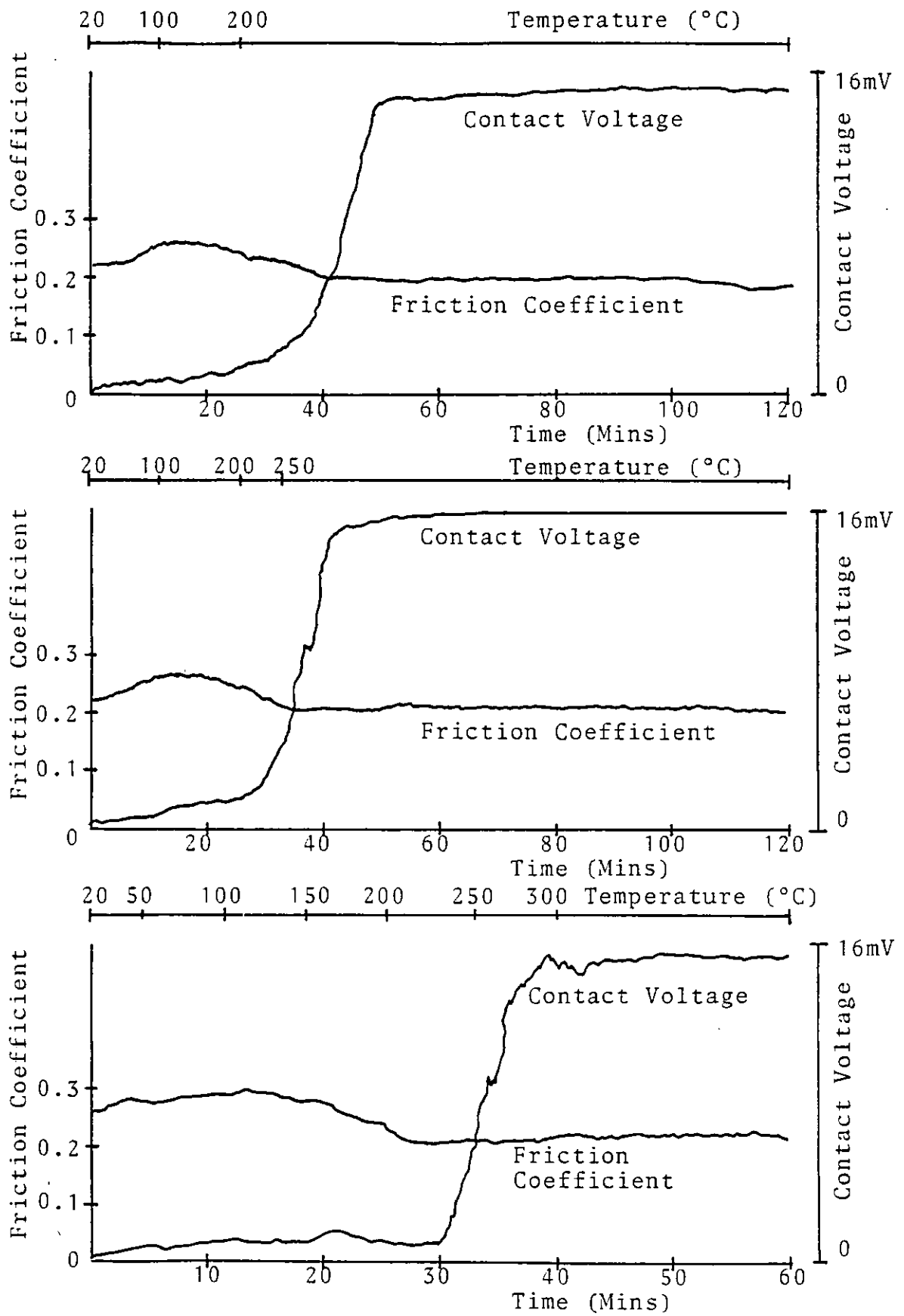


FIGURE 5.21 B2 + 0.4%C(w/w) at 200°C, 250°C, 300°C (drip feed)

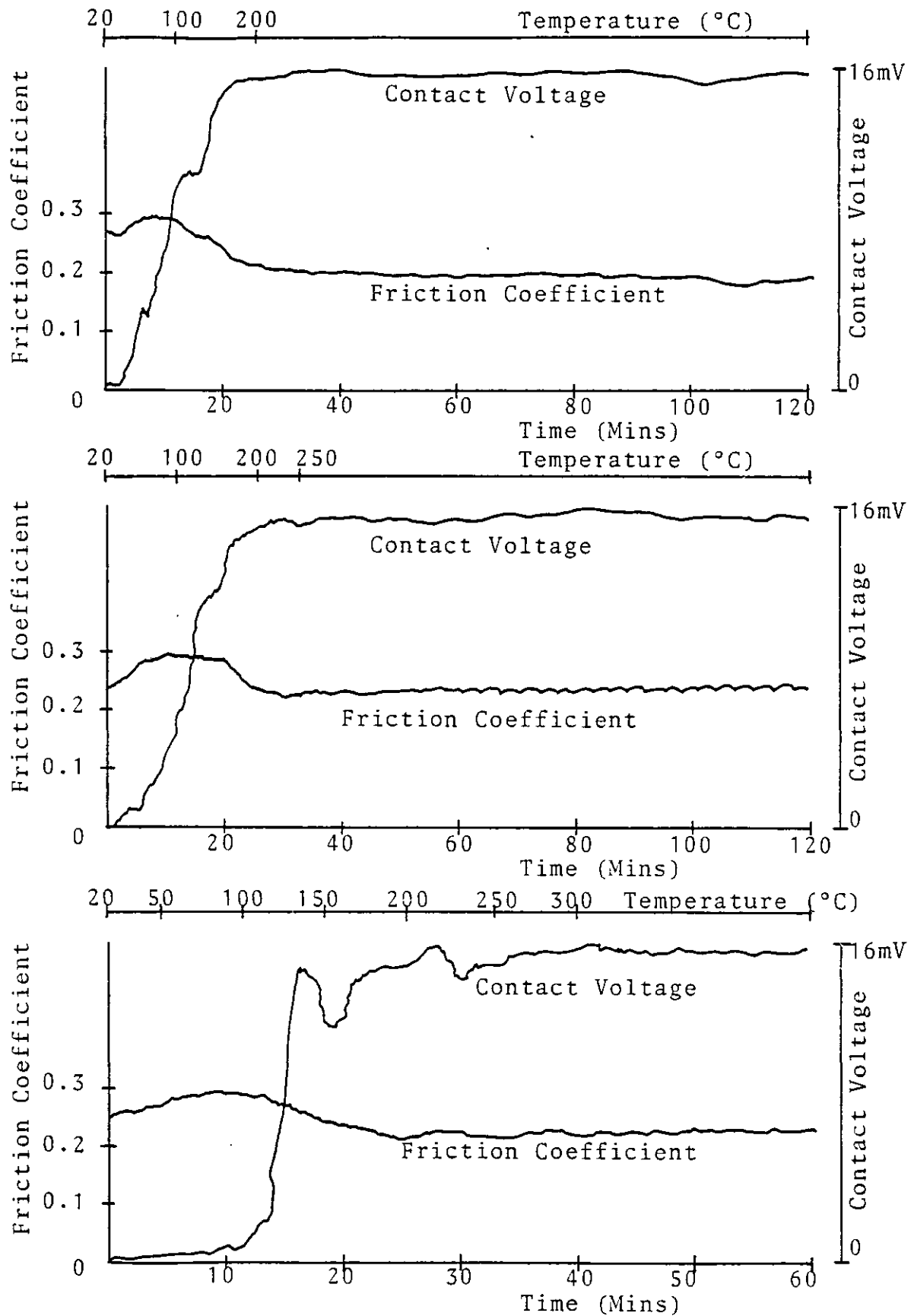


FIGURE 5.22 B2 + 0.5%C(w/w) at 200°C, 250°C, 300°C (drip feed)

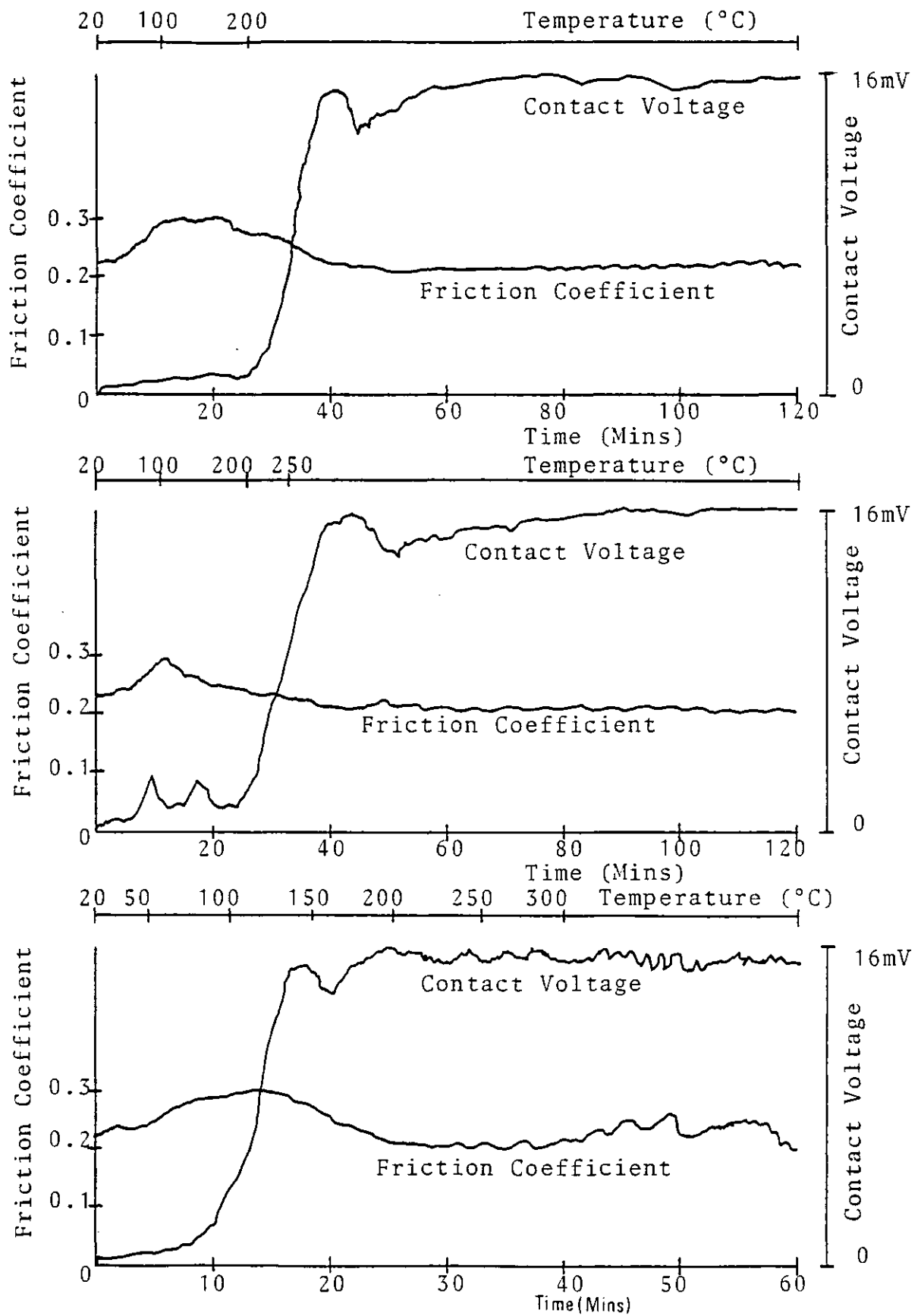


FIGURE 5-23 B2 + 0.75%C(w/w) at 200°C, 250°C, 300°C (drip feed)

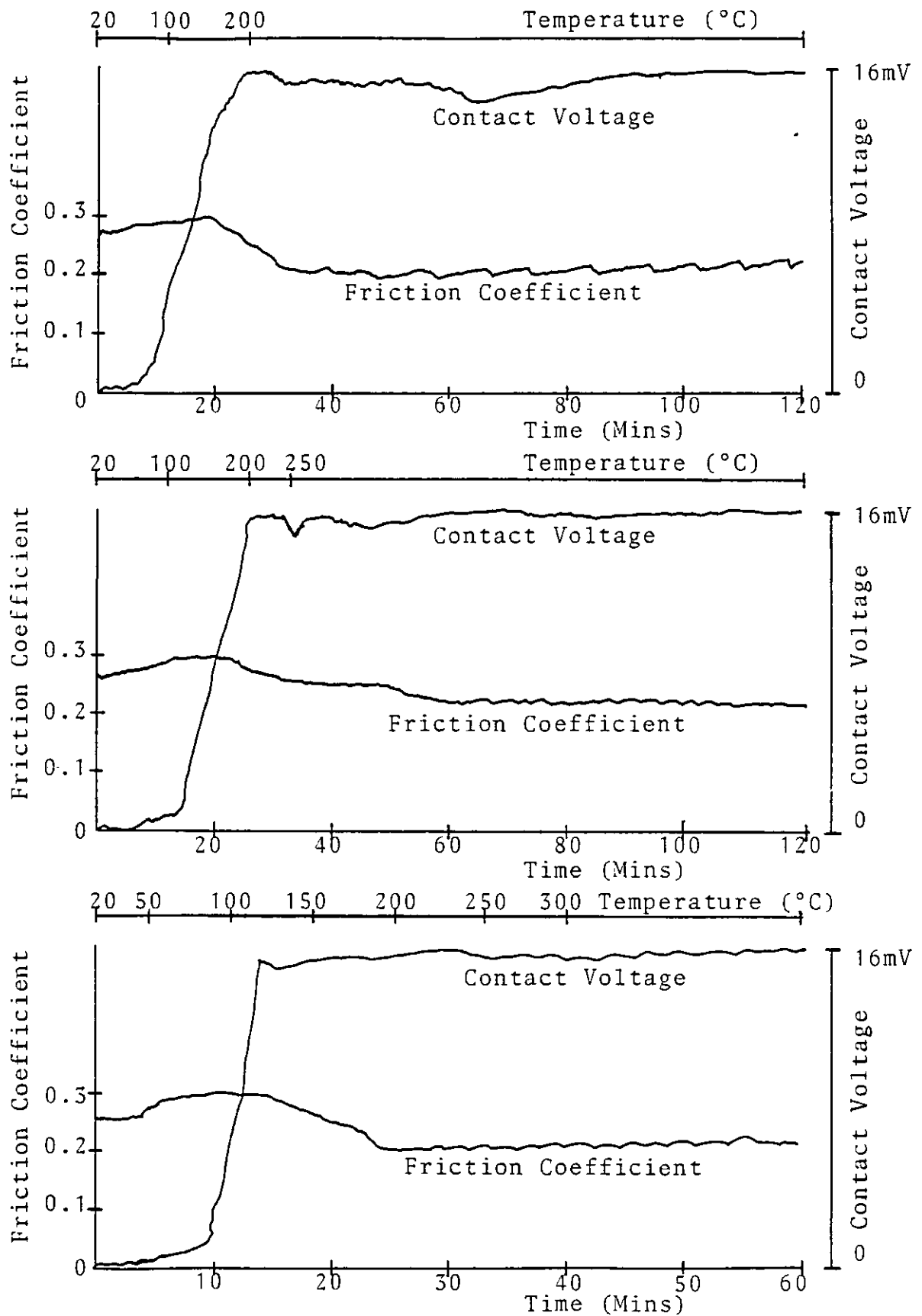


FIGURE 5.24 B2 + 1%C(w/w) at 200°C, 250°C, 300°C (drip feed)

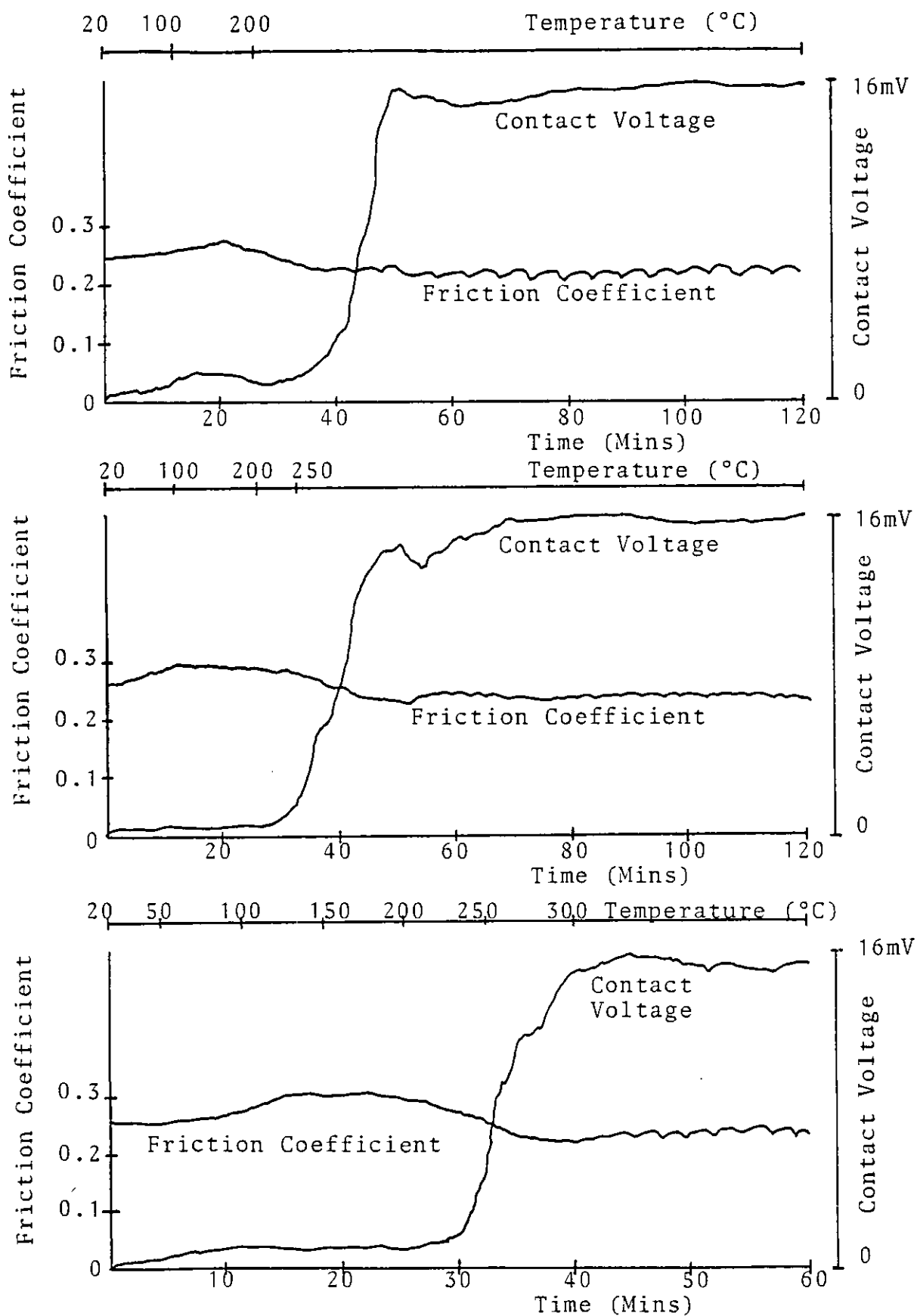


FIGURE 5.25 B2 + 2%C(w/w) at 200°C, 250°C, 300°C (drip feed)

again by the 'saw-tooth' profile of the friction coefficient.

### Deductions

1) There is evidence from the friction coefficient trace that at concentrations above 0.75%, and for all temperatures, the friction coefficient has a tendency to be unstable. The 'saw tooth' profile is indicative of a cyclic wear pattern and this is particularly noted at high concentrations of the additive.

2) The 0.25% and 0.5% concentrations established thick boundary oil films very quickly after the start. The friction coefficient for both these oils, and the 0.4% concentration, are more stable than the other oils. The reason for the 'saw-tooth' profile at 250°C for the 0.5% concentration is not clear.

3) Once again the effect of the additive when compared with the base stock is very marked. The friction coefficient has been made more stable and a thick film has been established in every test, particularly at high temperatures (300°C).

4) It is not possible to rank the oils in order of bore polishing severity. However oils

of 0.25%, 0.4% and 0.5% would be expected to perform better than the other oils, since these had stable friction coefficient traces and thick boundary films grew quickly.

#### 5.3.2.2 Visual S.E.M.

The visual examination of the H.F.R. liner surfaces for the drip feed base stock oil experiments is represented by the photographs on pages 212 to 214 . Again a number of points can be made.

- 1) The liner lubricated with the 0.4% concentration had a well defined honing pattern whilst low and zero concentration oils (e.g. B2) and high concentration oils (e.g. 1% and 2%) had a lack of this pattern and were clearly heavily polished. This is illustrated in figures 5.26 to 5.28.
- 2) The effect of temperature was less significant than for the immersed contact tests. Figures 5.29 and 5.30 illustrate this. The amount of surface smoothening in each case is approximately the same.
3. The effect of inclining the apparatus is a reduction in the amount of surface smoothening. This is illustrated by a comparison of figures 5.8 and 5.26 . The reason for this was thought to be the generation of thicker and more stable boundary films.



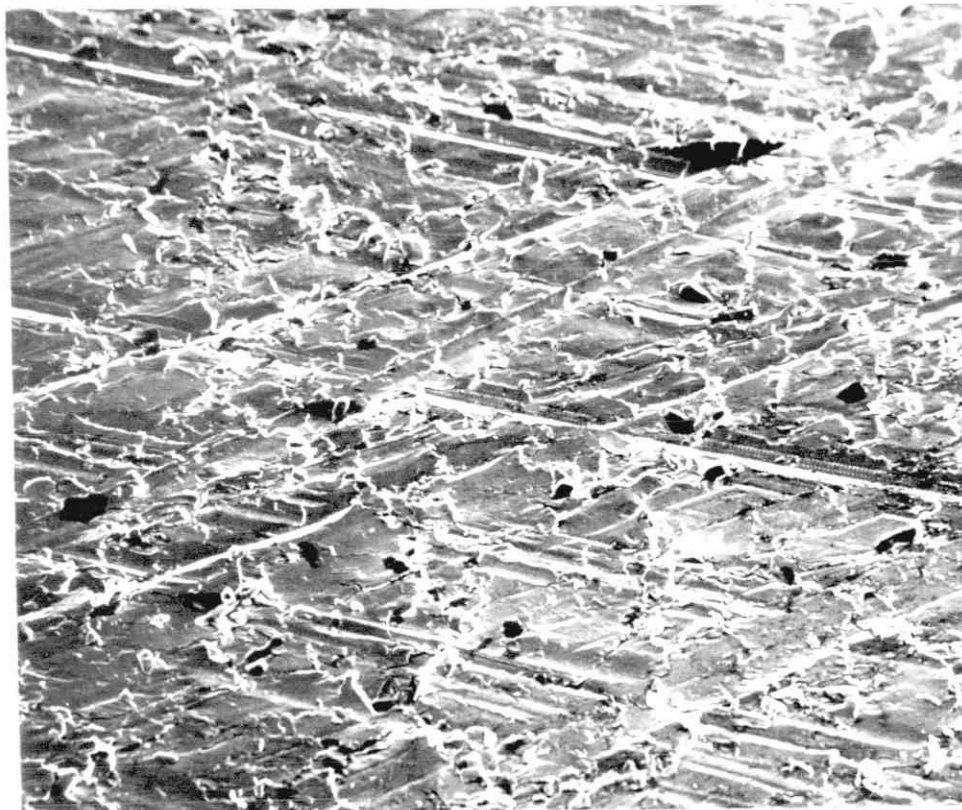


Figure 5.26 S.E.M. View of Liner with  $B_2+0.4\%C^{(w/w)}$  at  $250^{\circ}C$   
(Drip Feed). (200x)



Figure 5.27 S.E.M. View of Liner with  $B_2$  at  $250^{\circ}C$   
(Drip Feed). (200x)

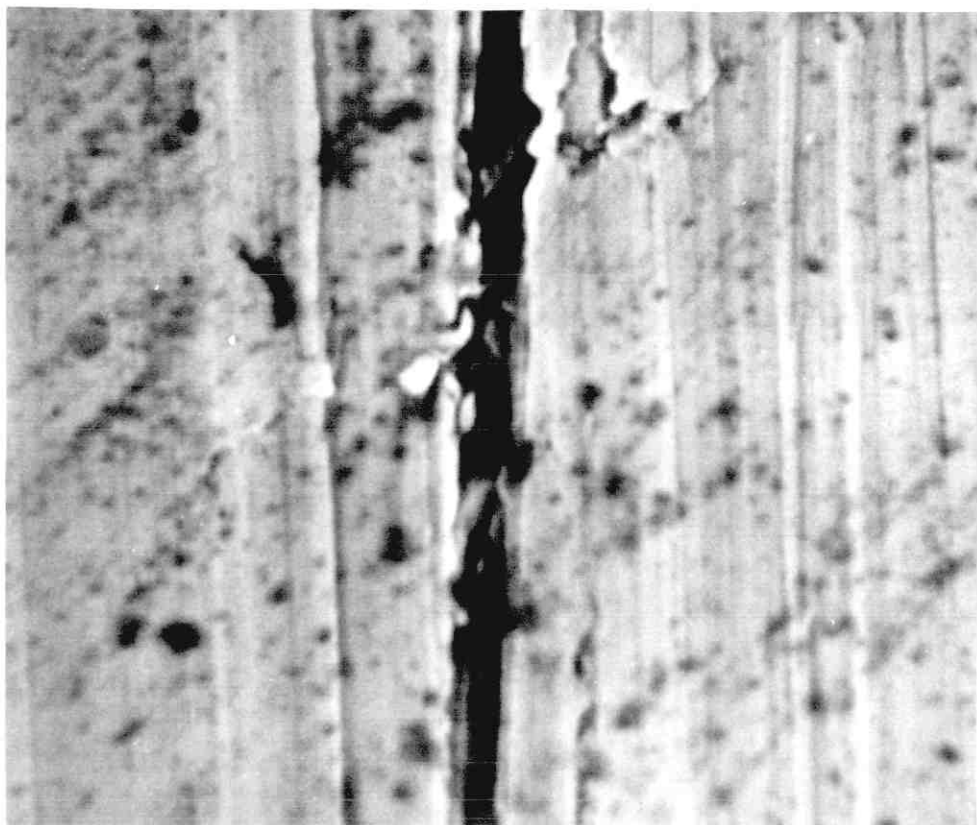


Figure 5.28 S.E.M. View of Liner with B2+1%C<sup>(w/w)</sup> at 250°C  
(Drip Feed). (200x)



Figure 5.29 S.E.M. View of Liner with B2+0.5%C<sup>(w/w)</sup> at 250°C  
(Drip Feed). (1000x)

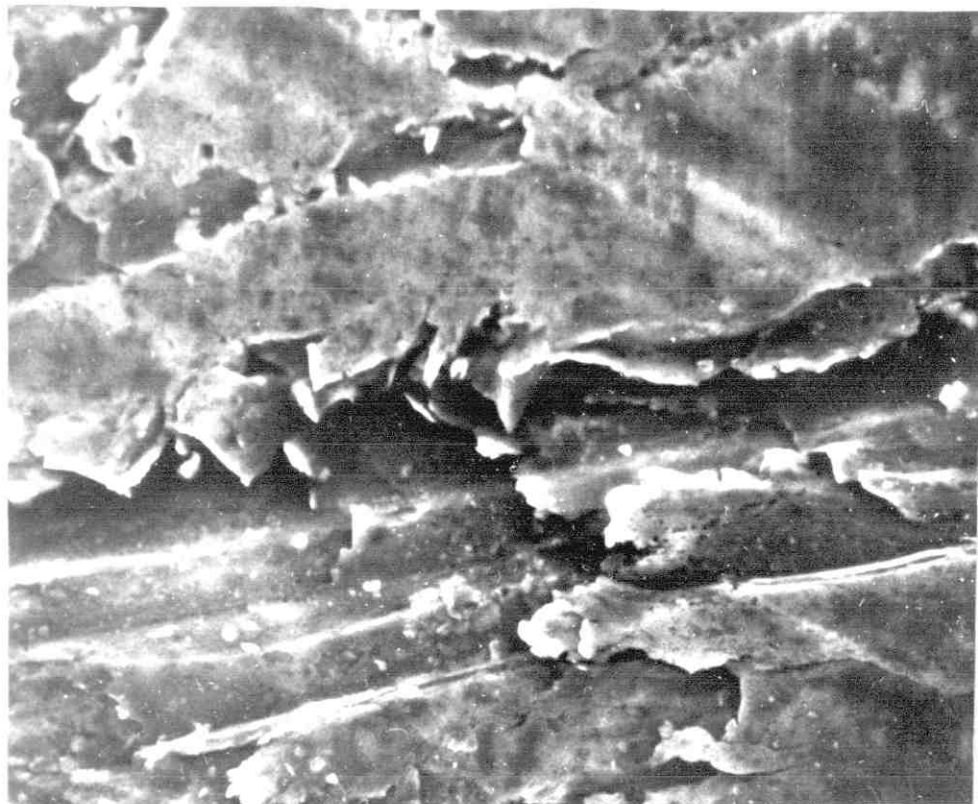


Figure 5.30 S.E.M. View of Liner with B2+0.5%C<sup>(w/w)</sup> at 300°C  
(Drip Feed). (1000x)

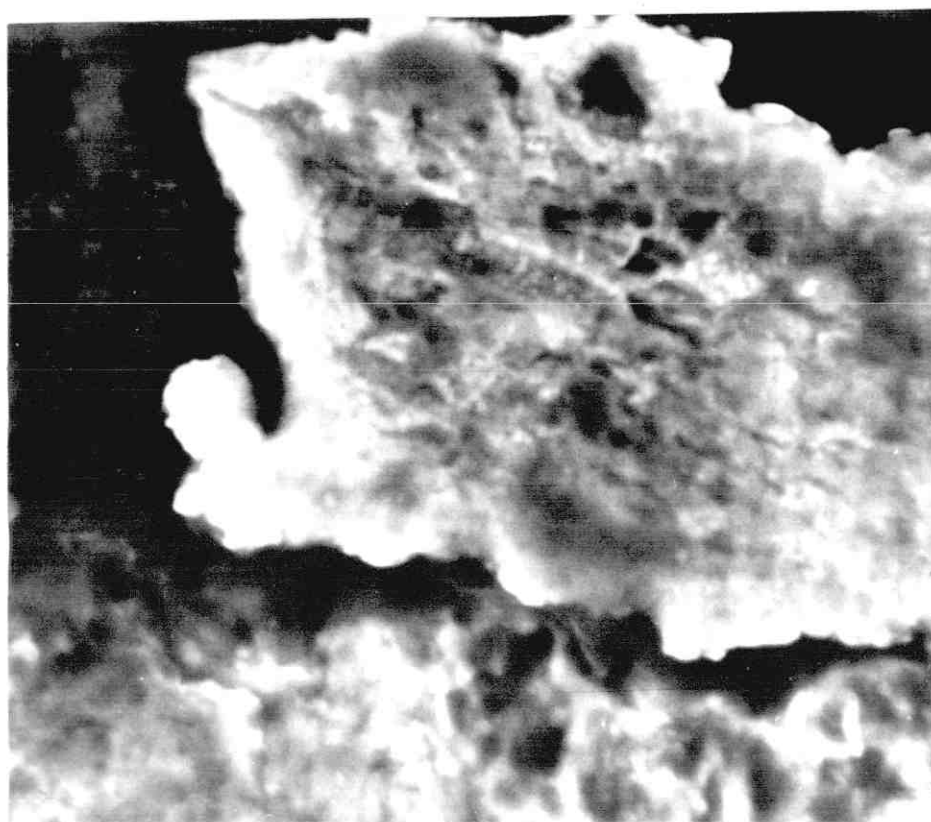


Figure 5.31 S.E.M. View of Liner with B2+1%C<sup>(w/w)</sup> at 300°C  
(Drip Feed). (5000x)

The friction plots shown in sections 5.3.1.1 and 5.3.2.1 indicate that, generally speaking, the drip feed contact voltage traces are more stable particularly towards the end of the test.

4) There was some evidence of plastic deformation, again most readily observed in the region of the honing pattern, as in figures 5.29 and 5.30. For H.F.R. liners with no honing pattern (as in figure 5.27) it was necessary to prepare micro-sections in order to investigate whether the honing pattern had been 'filled-in'. This is described in the next section.

5) Figure 5.31 is a high magnification view of a probable delamination particle in the process of delaminating from the surface. These were observed on highly polished surfaces only. A ferrographic analysis was conducted to confirm the presence of these particles in the oils producing high polish (Section 5.3.2.5).

6) There was limited evidence of abrasive scratch lines on the surfaces of some liners. For the heavily polished liners, as in figure 5.28, there was evidence of deep grooves in the sliding direction (top to bottom). There was some evidence on non-heavily polished liners, as in figure 5.29, but these scratch lines are clearly not as deep. On the liners with well defined honing patterns,

as in figure 5.26 , there was no evidence of these scratch lines.

#### 5.3.2.3 Micro-sectioning

This section describes the investigation of drip feed base stock oil liner micro-sections.

Figure 5.32 is a transverse micro-section (sliding direction into the photograph) of a non-heavily polished liner specimen. There is some evidence of cracking on the surface, although this does not extend beyond 100  $\mu\text{m}$ .

Figure 5.33 is a transverse micro-section of a heavily polished liner specimen. There is extensive cracking to a depth of 250  $\mu\text{m}$ . The mottled appearance of the subsurface is due to cotton wool which probably became attached to the liner section when it was cleaned with alcohol and dried with cotton wool.

As in previous microstructural studies in this thesis the heavily polished liner has clearly greater subsurface deformation than the non-heavily polished liner. There was no evidence of a white layer, glaze or 'filling-in' process on any liner examined. It is clear, again, from this investigation that heavy polishing is a high stress process, producing greater deformation than that observed for non-heavily polished liner specimens.



Figure 5.32 Transverse Micro-section of Liner with B2+0.75%C(<sup>w</sup>/w) at 250°C(Drip Feed). (200x)

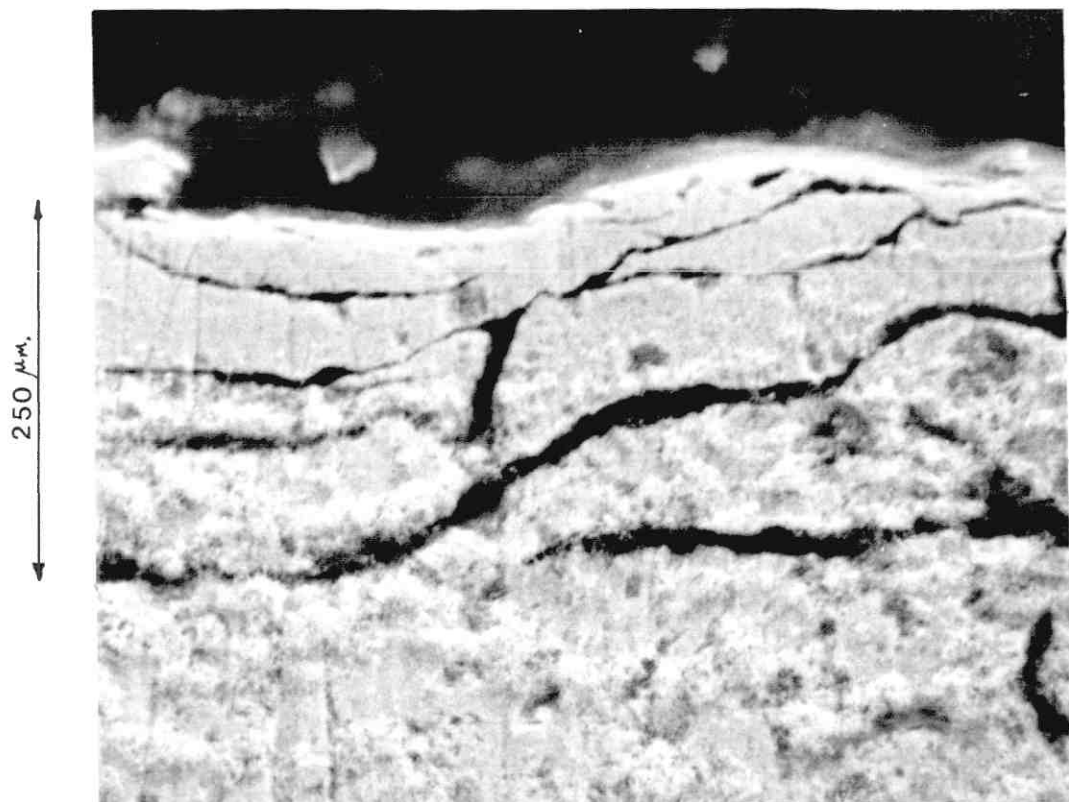


Figure 5.33 Transverse Micro-section of Liner with B2+1%C(<sup>w</sup>/w) at 250°C (Drip Feed). (200x)

#### 5.3.2.4 Microprobe analysis

This section describes the microprobe analysis of test liners from drip feed base oil experiments.

Figure 5.34 shows the Silicon : Sulphur peak ratios for cavities on each liner surface. There is clearly a correlation between high sulphur and high concentration. In addition a minimum sulphur trace was found with the oil producing the least polishing, i.e. B2 + 0.4% C(w/w). Figures 5.35 and 5.36 are two m.p.a. plots representing this data. Spot and area analyses of the surfaces of each liner did not reveal traces of elements other than those associated with the cast iron (e.g. Fe, Si, Mn, Cr were observed for the untested liner, figure 4.18).

The association between highly polished H.F.R. liners and sulphur in their cavities (but nowhere else) is again indicated. As in the previous microprobe analyses this presence of sulphur might be explained by elemental sulphur being associated with highly stressed areas and also the removal of an iron sulphide layer by the action of the piston ring.

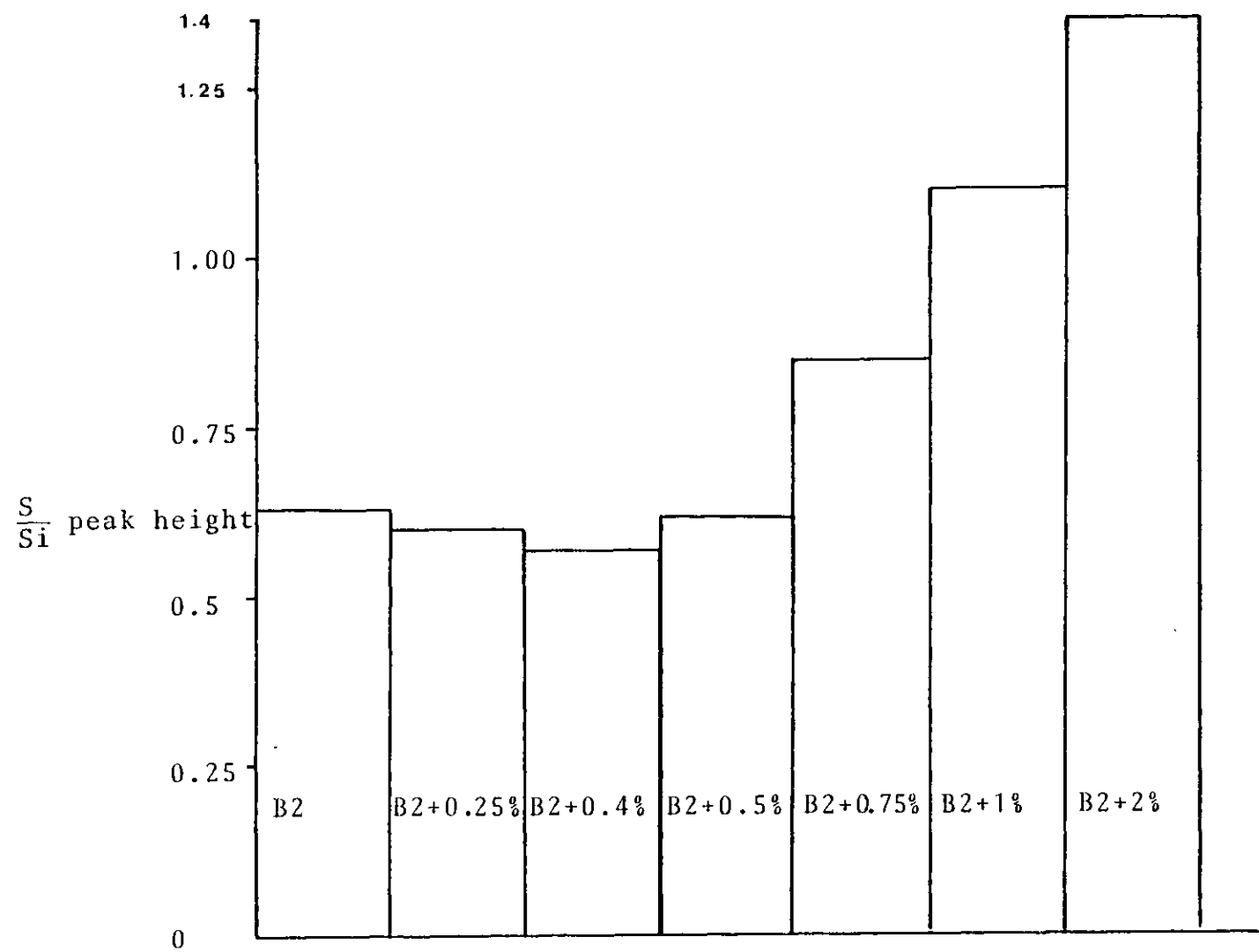


Figure 5.34 Ratio of  $\frac{S}{Si}$  Peak Heights for Each Concentration



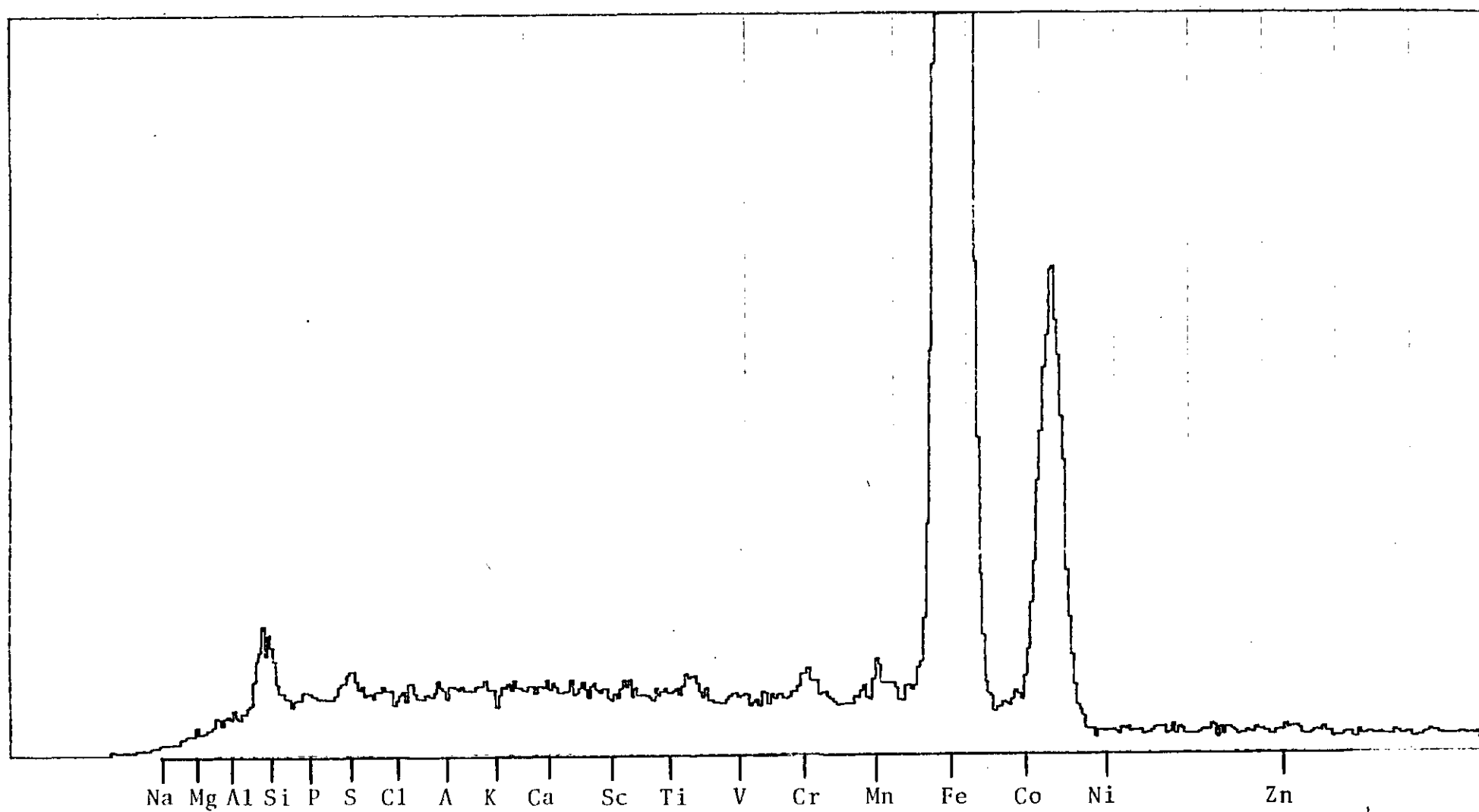


Figure 5.35 M.P.A. of Liner Cavity with B2 + 0.5%(w/w) at 250°C (spot)

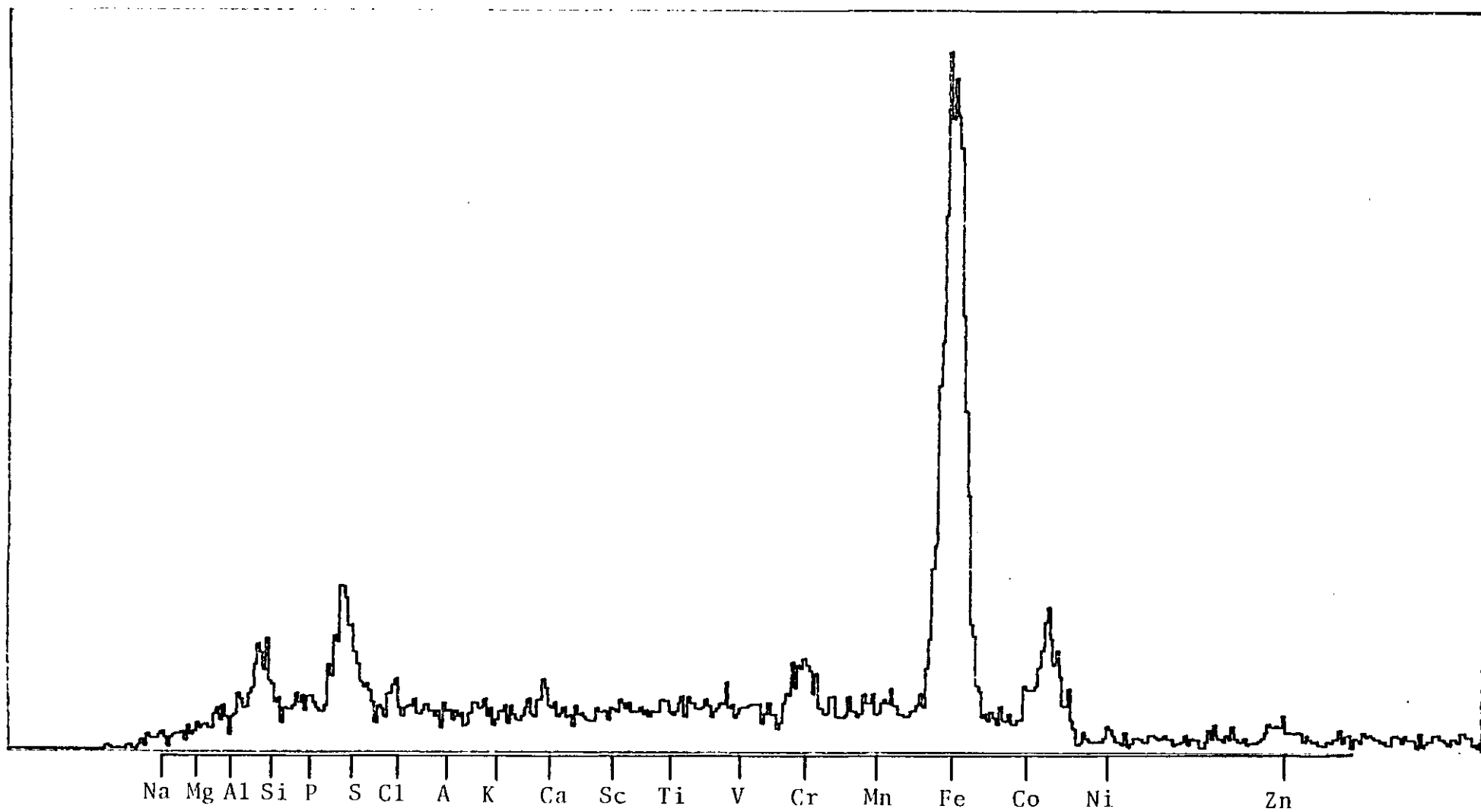


Figure 5.36 M.P.A. of Liner Cavity with B2 + 2%(w/w) at 250°C (spot)

#### 5.3.2.5 Ferrography

As in the previous chapter, a ferrographic analysis was carried out, to gain further information on the wear mechanisms relevant in this study.

Figure 5.37 shows a number of stringers, composed of swarf-like cutting debris. This was associated with heavily polished liner oil specimens only, and could be indicative of an abrasive wear process. Figure 5.38 also shows a number of these stringers and also a few possible abrasive contaminants which may be responsible for this production of abrasive wear debris.

The presence of delamination wear was investigated by the S.E.M. Figure 5.39 shows probable delamination wear particles, similar in morphology to those seen in section 4.3.2.5. Again these were not seen with oils from non-heavily polished H.F.R. liners. The morphology of these particles is similar to that of particles seen on the liner specimens.

The ferrographic analysis has shown that a wear debris similar to delamination wear particles has been observed as well as probable cutting wear debris. A number of small metallic particles were observed and could be the cause of the abrasive cutting wear particles. These small particles could be formed from disintegrated platelets or could be corrosive wear debris.

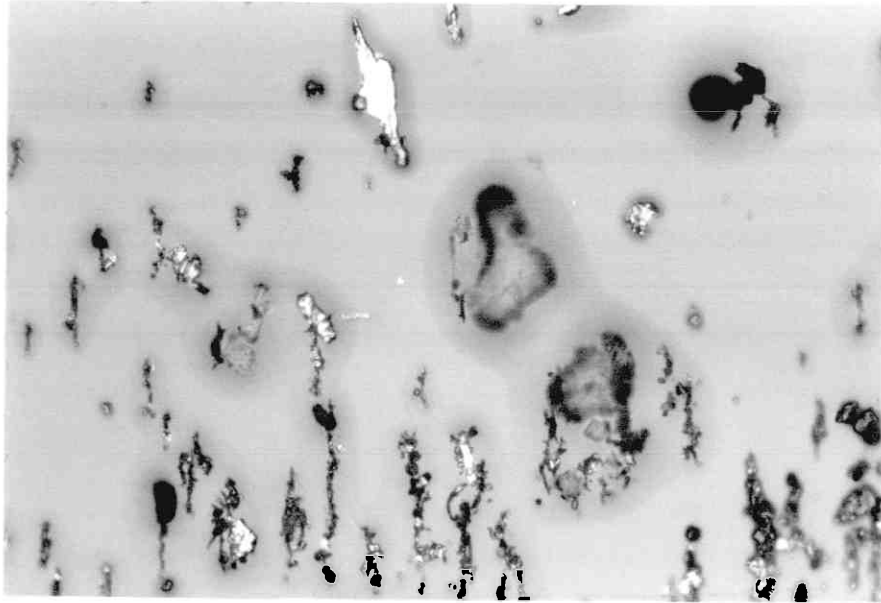


Figure 5.37 Optical View of Ferrogram. B2+1%C(<sup>W</sup>/w) at 250°C  
(immersed) (440x)

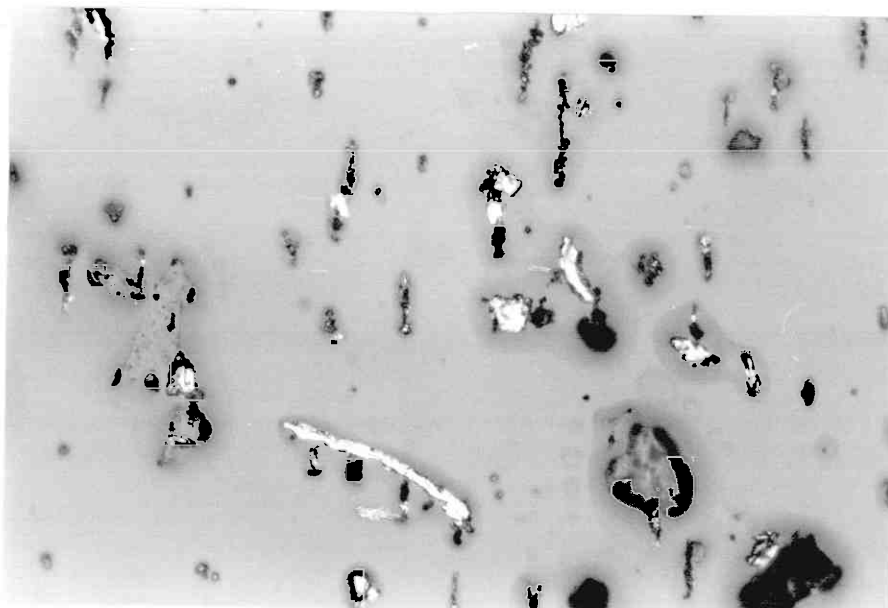


Figure 5.38 Optical View of Ferrogram. B2+1%C(<sup>W</sup>/w) at 250°C  
(immersed) (440x)

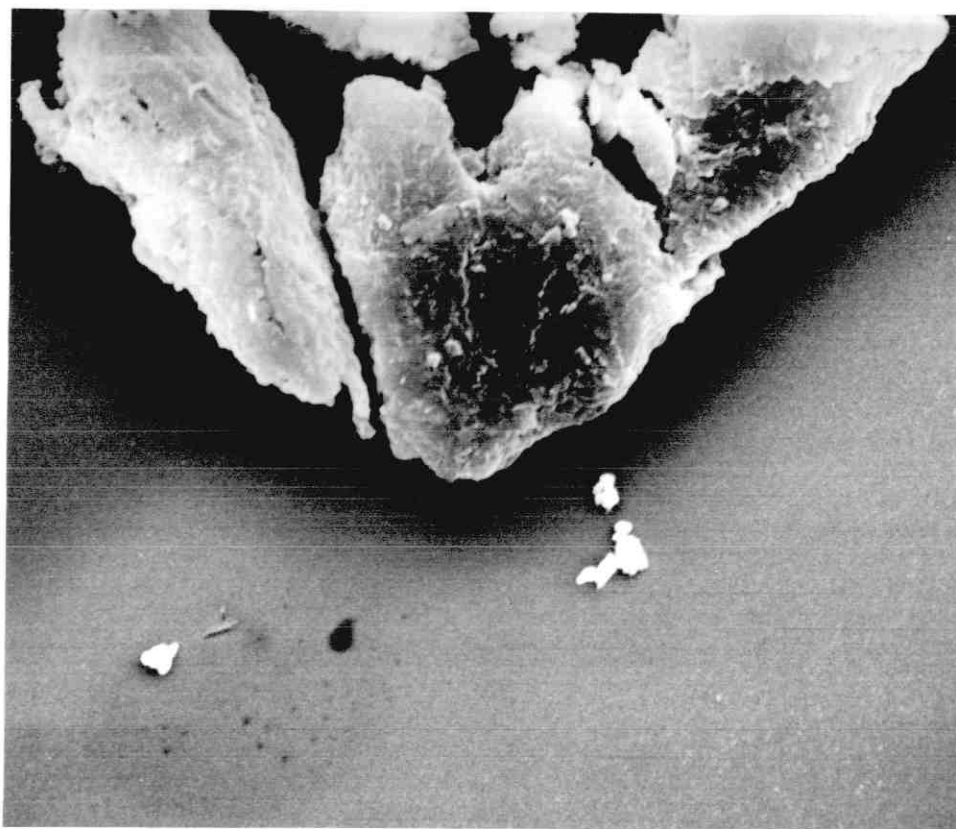


Figure 5.39 S.E.M. View of Ferrogram. B2 at 250°C (Drip Feed (2000x)

To investigate further the possibility of these particles being corrosive wear particles a microprobe analysis was conducted on many small particles. There was no evidence to link sulphur with these particles, although the sulphur may have been removed by the abrasive action of these particles. Consequently no positive indication of corrosive wear particles was obtained but it was not thought that this proved the absence of these particles.

#### 5.4 Discussion

The aim of the study conducted in this chapter was to carry out H.F.R. tests on a controlled set of lubricants. In particular the role of ZDDP concentration was the subject of the investigation.

From this study a number of points emerged.

##### 1) Polished Surfaces

As in the previous chapter, it was observed that polished or smooth surfaces were characterised as being highly stressed, associated with liner material removal rather than 'filling-in' or glaze formation and chemical analysis showed sulphur present in the cavities of polished surfaces only. In addition, there was no evidence of a white layer formation despite the presence of plastic deformation on many surfaces. This could be due

to the lack of incidence of scuffing, with which the layer is more usually associated.

As in the previous chapter these facts correspond with observations in full scale engine tests. This is a little surprising since no combustion products were used in any tests. Clearly the role of lubricant, additives and piston ring interaction is of considerably more importance than indicated in the literature on bore polishing.

## 2) Effect of ZDDP additive

The ZDDP additive clearly moderates the level of surface damage and polishing which was observed with the base stock alone. However there appears to be an optimum value of concentration, at which the amount of smoothening of liner surfaces and also the amount of subsurface deformation is a minimum. At low and high values of concentration the polished surfaces are once again associated with sulphur in the cavities. This may indicate, as in the previous chapter, that polishing is an E.P. phenomenon, not antiwear, with the generation of an iron sulphide film. This could lead to surface attack by a combination of the three wear processes mentioned in the last chapter, namely corrosive, abrasive and delamination wear. Of these, corrosive wear is likely to be the most dependent on ZDDP concentration, since the

oil's sulphur content is clearly influenced by ZDDP concentration.

At low concentrations, oxidation probably occurs rapidly in the absence of ZDDP antioxidant. This could lead to corrosive oxidation products which would assist in the smoothening of the surface. The sulphur peak observed for the liner lubricated with the base oil is smaller than that seen on other liners devoid of honing pattern. It is possible that the sulphur in the base oil could contribute a small E.P. component, as mentioned on Page ( 20 ), and this may be responsible for a corrosive wear process. The quantity of sulphur in the base oil would, however, be less than that found in the remaining control oils.

At high additive concentrations (e.g. 2%) sulphur concentration in polished liner cavities is clearly much greater than for lower additive concentrations (eg. 1%). This could indicate that, even for two heavily polished surfaces, the higher the ZDDP concentration the higher the sulphur trace. This probably indicates that higher concentrations are more associated with E.P. action and possibly corrosive wear. This is supported by visual observation of the liner surfaces by S.E.M. where high temperatures and high concentrations produced a mottled surface appearance, indicating possible corrosive attack (Figure 5.10). A reason for this association between



high concentrations and E.P. action could be the antioxidant properties of ZDDP's, causing a decrease in boundary film thicknesses and initiating an increase of surface stress and temperature thereby accelerating the likelihood of corrosive wear. (And subsequently polishing).

The 0.4% concentration appears to be an optimum value between the detrimental and beneficial aspects of thick boundary films. The stable friction trace for the 0.4% concentration indicates no cyclic wear pattern, compared with higher concentrations. This data agrees very well with a much fuller study of the mechanisms of ZDDPs published this year ( 66 ).

This study would confirm earlier work by Georges et al ( 4 ) who concluded that plastic deformation was increased by the addition of the ZDDP additive. However, as in Georges' study, the mechanism of this is not clear.

### 3) Effect of temperature

As in the previous chapter it was observed that higher temperatures generally indicated less stable friction coefficients and lower average contact voltage readings, particularly at high concentrations. Scanning electron microscopy of the liner surfaces also suggested

that lubricants appeared to produce slightly more plastic deformation at higher temperatures.

Since the reaction rate of the E.P. film formation is strongly influenced by temperature, it is not surprising that higher temperature tests are associated with greater smoothening of the surface, since wear rate is greatly influenced by the rate of film formation. This effect was not observed as being very severe.

#### 4) Effect of drip feeding

There was a general tendency for friction coefficients to become more stable, and in the majority of cases to be reduced, for the drip feed tests. In addition it was observed that, in general, the contact voltage traces had higher values for longer periods than the corresponding immersed tests. Also the visual S.E.M. indicated that for drip feed test liners, the amount of surface smoothening or polishing was less than the corresponding immersed tests. This could be due to oil insolubles being present in the immersed tests, as described by Parsons ( 37 ).

These observations may be due to more rapid oxidation of oil droplets in the drip feed case, causing the formation of a thick polar film,

possibly on top of existing antiwear or E.P. films. These would tend to be more easily sheared, reducing friction and also appear on the contact voltage output as a thick film. This film, as mentioned previously, cannot be a varnish since the contact voltage quickly fell to zero when the vibrator was suddenly switched off.

There was no evidence in the literature of an investigation into the effect of ZDDP concentration on bore polishing and consequently no direct comparisons with previous work can be made. However, the vast amount of literature on ZDDP mechanisms do indicate agreement with some of the observation made e.g. corrosive effect of high concentrations, antioxidant behaviour, increase of plastic deformation and existence of optimum concentration. Clearly in fully formulated lubricants, the effect of ZDDP concentration on polishing is complicated by the addition of detergents, dispersants, V.I improvers and so on. However, this chapter has indicated the importance of the concentration of this additive upon the phenomenon of bore polishing and further suggested a possible method by which polishing could be initiated by the ring/liner interaction. The relative importance of this proposed mechanism of bore polishing is not clear when compared to the other possible mechanisms (Page (38)), although it is hoped that

the role of the piston ring in bore polishing has been highlighted by this study. In addition it is suggested that the choice of piston ring profile, metallurgy and surface finish of the liner and concentration of ZDDP in crankcase lubricants merit greater importance in the investigation of methods to reduce bore polishing.

### 5.5 Conclusions

As in the previous chapter a number of conclusions may be drawn from the study conducted.

1) The heavily polished surfaces were found to be characterised by :

a) Severe stress, evidenced by subsurface deformation.

b) No evidence of white layer formation, glazing or 'filling-in' of honing pattern. This implies that the polishing process removes material.

c) Very little evidence of surface deposits on any liner surfaces, but sulphur was found in heavily polished liner cavities.

2) The ZDDP additive, in isolation from other additives, had a marked effect on the occurrence

of bore polishing. In particular :

- a) At zero and low concentrations ( $<0.25\%$ ) smooth surfaces were observed. It is suggested that, in the absence of antioxidant effects of ZDDP, corrosive oxidation products assist in the smoothening of the surface.
- b) At high concentrations ( $>1\%$ ) smooth surfaces were obtained. This may indicate the corrosive nature of ZDDPs acting under E.P. conditions.
- c) At medium concentrations, e.g.  $0.4\%$ , a compromise between these two extremes was thought to occur.
- 3) Plastic deformation was found to be linked to ZDDP concentration. In particular smooth, deformed, surfaces were observed at higher concentrations. The mechanism of this action was not clear.
- 4) There was a limited amount of evidence of abrasive wear. This was not associated with the least polished surfaces and seemed more relevant to smoother liner specimens. Cutting wear debris was also detected.
- 5) A number of sheet-like particles were seen on heavily polished liners but not on least polished

liners. These were thought to be similar to delamination wear particles and are indicative of a cyclic stress region. Their presence was confirmed by ferrography.

6) The presence of sulphur in polished liner cavities was thought to indicate that polishing was by an E.P. action, in which the repeated removal of a reacted iron sulphide layer could be responsible for wear by chemical corrosion. This was thought to increase the likelihood of abrasive wear.

7) High temperatures were associated with less stable friction and contact voltage traces. Visual S.E.M. also indicated that slightly more plastic deformation occurred at higher temperatures.

8) Drip feeding was seen to stabilise and reduce friction coefficients and increase the likelihood of thick boundary films. As a result it was also observed that the severity of smoothening of the surface was less in this case, compared with the immersed contact tests.

9) The importance of lubricant, additives and piston ring/liner interaction was highlighted from this study, although the importance of these factors in relation to other possible mechanisms

was not apparent. The properties of the materials used e.g. strength, ductility and surface finish are clearly of great importance.

C H A P T E R 6

General Discussion



## CHAPTER 6

### General Discussion

#### 6.1 Introduction

This chapter discusses the relationship between the results obtained in this study and existing theory and practice. In particular it attempts to define the nature of a bore polished surface, discuss possible mechanisms of polishing and place bore polishing in the context of serviceability of a diesel engine.

#### 6.2 General Discussion

A phenomenon closely resembling bore polishing in diesel engines was obtained using the H.F.R. apparatus. This resemblance had four significant forms :

- 1) Visual appearance of liner surfaces.

Heavy polishing observed in practice is associated with large scale exposure of the graphite flake structure of the cast iron. This was noticed with heavily polished H.F.R. specimens also, as described in Chapter 3. In addition the H.F.R. apparatus demonstrated its ability to 'screen' potentially high bore polishing lubricants. Oils of high bore polishing percentages clearly produced

more polishing on H.F.R. liner specimens than oils of low bore polishing percentages.

## 2) Liner subsurfaces

Both H.F.R. liner specimens and actual liners showed similar subsurface deformation. For heavily polished engine test liners the deformation was more extensive, reaching greater depths than that seen for H.F.R. liners. This suggests that the H.F.R. test does not produce an exact simulation of the lengthy engine test, although it correlates well with such tests.

## 3) Surface profile

The Talysurf profiles for heavily polished H.F.R. liners and heavily polished engine test liners had two important similarities.

- a) Closely corresponding C.L.A. values
- b) Similar appearance of surface profile

One important drawback of using surface profile analytic techniques, of which C.L.A. values are the simplest, is that a long sample length is desirable. (Typically not less than 5 mm). However the wear scars obtained for the H.F.R.

tests were only 1 mm in length and this effectively meant that a more detailed profile analysis was not possible.

4) M.P.A.

A chemical analysis of H.F.R. test liners and engine test liners indicated that significant traces of sulphur were found in cavities on heavily polished liners but nowhere else. This also agrees with previous work on the Petter AVB diesel engine ( 62 ).

The resemblance indicated between H.F.R. specimens and engine test liners is clearly important if any conclusions can be usefully derived from this study.

From the techniques employed in this study there are clearly a number of factors associated with a heavily polished surface. In particular these are :-

- 1) Removal of surface layers by a variety of wear processes (discussed later) rather than the 'filling-in' of honing pattern as described by Sreenath and Ramon ( 35 ). This was indicated by talysurf profiles and micro-sections prepared for a number of worn specimens.

- 2) Subsurface deformation was particularly

noticeable with heavily polished specimens, indicated by subsurface cracking around the graphite structure. The presence of delamination-like particles and cutting wear particles also indicated that the heavily polished surfaces were more severely stressed than the non-heavily polished surfaces. This agrees with the study carried out by Ayel et al (62), who examined micro-sections of a heavily polished liner from a Petter AVB turbocharged diesel engine.

3) A chemical analysis of the heavily polished surfaces indicated no overall change in composition. This is confirmed by Godfrey (67). However when cavities in the liner surfaces were analysed it was clear that an excess of sulphur was present. This was not found with non-heavily polished specimens, original liners or unrubbed liners, and appeared to be associated with heavily polished surfaces only.

This observation was confirmed by analysis of actual engine liners where strong traces of calcium were also indicated. This agrees with Ayel et al (62).

4) The heavily polished surfaces gave some indication of the possible wear mechanisms involved. There was some evidence of abrasive wear (scratching of the surface), corrosive wear

(pitting of surface), plastic deformation (flow of surface material) and delamination wear (plate-like particles). Abrasive wear has been reported by several authors ( 33,39,67) although there is no evidence of the other wear mechanisms in the literature. This could be due to the very limited amount of literature available on this topic.

5) There was no evidence of a glaze or coating on the surface of any liner. This phenomenon appears more closely related to scuffed areas and there was no evidence of scuffing in the tests conducted, although Nadal and Eyre ( 6 ) found no evidence of white layer formation on liners with heavy wear. There was no evidence of glaze or other forms of layer formation in the literature on bore polishing, although the Paramins Report ( 20 ) mentions that in rare cases polishing and glazing have been found in one engine.

From the study conducted in this thesis it is thus clear that there are a number of similarities between the simple tests carried out and actual practice. This is somewhat surprising since no combustion products were present in the H.F.R. tests. The implications from this fact are :

1) The lubricant and additives have a crucial role

to play in the process of bore polishing.

2) The piston ring/cylinder action may be of greater importance than granted in the literature. In particular, metallurgy and surface finish of these components are of particular interest if the phenomenon is to be alleviated.

The importance of these points is partially mentioned in the literature with run-in condition of liner and piston ring interaction being noted. However the effect of specific lubricant additives, materials and surface finish as well as some wear mechanisms have not been clearly associated with bore polishing. The importance of surface finish and lubricant composition was suggested as being relevant for methods of reduction of bore polishing, although little detail was found on the significance of different factors. (e.g. additive concentrations).

With regard to possible mechanisms of bore polishing the following points are tentatively concluded:

As indicated in the literature, bore polishing is a complex mechanism undoubtedly involving many different factors. It is fundamentally a wear process and several types of wear have been identified, namely, abrasive, corrosive and delamination wear. The composition of the oil is of significant importance with

regard to these wear processes as indicated by chapters 4 and 5. In particular it is suggested that, since heavily polished surfaces are highly stressed, the formation and removal of an iron sulphide film leads to a corrosive wear process, as described by Watkins ( 3 ). This, in turn, may produce abrasive contaminant allowing abrasive wear to occur. In addition the high cyclic stress has been shown to produce delamination-like wear particles. These three processes appear critical in the removal of surface layers in the polishing process. The formation of smooth surfaces with less oil retention capability could indicate high temperatures as well as high stresses. This would undoubtedly increase the likelihood of corrosive wear by removal of the iron sulphide film. In this respect the presence of sulphur associated with heavily polished surfaces could strengthen this suggestion. The reasons for heavily polished surface oil films having less load carrying capacity is not clear from this study, however it was considered to be a significant point. The role of ZDDP concentration was investigated in a controlled sequence of tests and an optimum concentration (0.4% (w/w)) obtained. Polishing was thought to be due at low concentrations to corrosive oxidation products and at high concentrations to the corrosive wear by removal of the FeS film and also the lack of thick boundary films due to the antioxidant properties of ZDDPs. Again in these tests corrosive wear was thought to be important. Unfortunately there was little evidence in the literature of wear

mechanisms, other than abrasive wear, connected with bore polishing. Ayel et al ( 39 ) do, however, rule out corrosive wear due to acid attack.

There are a number of methods by which polishing could be alleviated, based upon the study conducted. These are :-

- 1) The use of harder, less ductile ring/liner materials.
- 2) A deeper honing pattern could extend the oil retention capability, particularly at long engine life.
- 3) The reduction of sulphur in the fuel and in the base oil could help a reduction in corrosive wear. In addition the ZDDP concentration has been shown to be important in this context.
- 4) Increasing the dimensions of the load carrying profile of the piston rings could reduce interfacial pressure and stress, thereby reducing the likelihood of delamination wear and corrosive wear.

It is necessary to place bore polishing in context of engine serviceability. The tests conducted indicate that oils of 20% bore polishing percentage give an acceptable liner surface, with honing pattern intact and low stress on the surfaces. However oils of 45% bore polishing percentage and above are clearly unacceptable.



For these oils it is likely that the generation of further high temperatures will lead to adhesive welding of the surfaces and eventually scuffing. The lack of oil retention ability with oils of 45% bore polishing percentage and above would cause blow-by and seriously affect compression ratio of the engine and consequently its efficiency. In the case of high polishing oils, various authors comment on the increase in oil consumption at the onset of serious polishing (14,33), this may also be important in an energy conscious society.

Finally mention should be made of the relevance of this study. The study conducted has highlighted several important and new facts about bore polishing. However a serious drawback of this study is that it cannot place the proposed mechanism of bore polishing in context with other mechanisms e.g. Crown land deposits. For this to be possible a more sophisticated bench test apparatus would be necessary to attempt to move nearer to actual practice. e.g. A test rig with combustion products might reveal more information on the mechanisms of bore polishing. Another important drawback of the tests carried out in this study is the size of the wear scar. This has meant that a full profile analysis could not be conducted. Furthermore, the quantity of wear debris for ferrographic analysis was very small.

However, this study is, to the author's knowledge, the first attempt to produce bore polishing in a bench

test device and to correlate results with practice. Despite its limitations, the study has highlighted a number of new and important facts associated with bore polishing.

CHAPTER 7

Conclusions and suggestions for further work

## CHAPTER 7

### Conclusions and suggestions for further work

#### 7.1 Conclusions

This chapter describes the conclusions of the study conducted and also suggests areas where the study could be usefully extended.

The conclusions have three forms:

##### a) General Scientific Conclusions

1) A phenomenon similar to bore polishing in diesel engines was produced in a simple reciprocating bench test apparatus. This resemblance took four specific forms:

(i) Visual appearance of liner surfaces.

Liner Wear scars examined from the H.F.R. test demonstrated, visually, a good comparison with liners taken from engine tests. In particular there was good correlation between H.F.R. and engine tests for liners with heavy polishing, in which the graphite structure of the cast iron was clearly exposed.

(ii) Liner subsurfaces.

Both H.F.R. test liners and engine test liners showed that heavy polishing is associated with severe stress, as evidenced by subsurface cracking around the tips of graphite flakes. This was not observed for lightly polished liner specimens, for which the honing pattern was still visible.

(iii) Surface profile.

Talysurf profiles of bench test liner wear scars and engine test liners bore significant resemblance. In particular C.L.A. values were comparable and also surface profiles had similar appearance.

(iv) Chemical analysis

A microprobe analysis of H.F.R. and engine test liner specimens demonstrated close similarity. In particular it was noted that in cavities on heavily polished surfaces there was significant traces of sulphur, whilst there was no such trace on lightly polished surfaces, unrubbed surfaces or untested liner surfaces.

2) An attempt to define a liner surface with heavy bore polishing was made. It was suggested that such a surface is associated with :

(i) A mirror-like appearance with surface roughness of less than  $0.12 \mu\text{m}$  (approximately  $5 \mu\text{in}$ )

(ii) Removal of surface layers, rather than the formation of a glaze, coating or white layer. There was no evidence that the honing pattern had been 'filled-in'.

(iii) Severe stress. Evidenced by cracking of subsurface up to a depth of  $200 \mu\text{m}$ .

(iv) Sulphur in cavities. Traces of sulphur were not observed on the surface of any liner or in cavities of lightly polished liners.

3) The visual examination of H.F.R. liner surfaces highlighted four phenomena specifically associated with heavily polished surfaces. Of these only abrasive wear had been previously reported. The phenomena observed were :-

(i) Plastic Deformation.

On many of the liners examined it was observed that the cast iron had been plastically deformed. This was most readily observed on liners where the honing pattern was visible. For liners where the honing pattern was not visible (on heavily polished liners) the subsurface was highly stressed.

(ii) Delamination Wear.

On heavily polished liner surfaces delamination wear particles were seen in the process of breaking away from the surface. Ferrography confirmed the existence of these particles and also indicated that they were of similar morphology to those seen on the liner surfaces.

(iii) Abrasive Wear

On a number of tested liner specimens there was evidence of scratch lines in the sliding direction. In addition swarf-like debris was detected by ferrography. These observations are indicative of abrasive wear, which was largely confined to heavily polished liner specimens.

(iv) Corrosive Wear

On a number of tested liner specimens there was evidence of possible corrosive pitting. This was associated, in general, with high temperature tests and also with lubricants of high ZDDP concentration in the base stock oil tests.

4) A possible mechanism of bore polishing was proposed relating to the removal of a reacted oil film by the piston ring. It was suggested that since heavy polishing is associated with high stress and high sulphur traces in liner cavities this could indicate the formation and removal of an iron sulphide oil film. This corrosive wear process was considered to enhance the likelihood of abrasive contaminant and hence abrasive wear. In addition the presence of delamination wear particles is indicative of a high cyclic stress process and these particles were considered to further enhance the likelihood of abrasive wear. In conclusion it was suggested that bore polishing is fundamentally a wear process, with corrosive, abrasive and delamination wear specifically implicated.

5) The effect of temperature upon the severity of liner polishing was noted. It



was observed that for high temperatures the H.F.R. liner surfaces exhibited greater plastic deformation than that seen for low temperatures. In addition the contact voltage traces were, in general, less stable at higher temperatures.

6) The effect of inclining the apparatus was also noted. Liner specimens when drip fed gave some indication that less polishing was achieved, when compared with the corresponding immersed test. This effect was considered to be due to the removal of accumulated oil degradation products with drip feed tests. The correlation between drip feed tests and immersed tests was found to be very good.

#### b) ZDDP conclusions

1) For the controlled ZDDP concentration tests, an optimum additive concentration of 0.4% (w/w) was found. It was observed that for this concentration there was little evidence of surface smoothening, no evidence of sulphur in the liner cavities and little subsurface cracking. In contrast, high concentrations ( $> 1\%$ ) and low and zero concentrations ( $< 0.25\%$ ) produced heavily polished surfaces with characteristics similar to those seen in engine tests.

Corrosive wear was thought to be responsible for the heavy polishing seen at low and high concentrations.

2) It was observed that for increasing concentrations of ZDDP additive (above 0.4% (w/w)) there was increasing plastic deformation.

c) Industrial conclusions

1) With regard to the serviceability of a working diesel engine it was suggested that bore polishing percentages of 20% or less are acceptable whilst 45% or more are unacceptable. The efficiency of the engine is of great importance and since this is closely linked to compression ratio (which is effected by blow-by) the onset of heavy bore polishing is clearly a problem worthy of further research in an energy conscious society.

2) The establishment of a simple bench test device which can produce an effect similar to bore polishing in an actual engine is clearly of industrial benefit. In particular the H.F.R. device has shown its ability as a lubricant screening device.

3) In order to place the proposed mechanism of bore polishing in perspective with other bore polishing theories it is clearly necessary to include combustion products in the H.F.R. apparatus. The absence of such products in this study is obviously a limitation on the conclusions reached.

## 7.2 Suggestions for further work

The study described in this thesis has highlighted a number of important and new facts associated with bore polishing. However there is clearly a need for increased investigation into bore polishing both in engine tests and bench tests. The scope for such investigation is vast since bore polishing is clearly a complex problem being influenced by metallurgy, surface finish, lubricant and additives, fuel, design factors and so on. The following suggestions for further work refer to the H.F.R. apparatus.

- 1) The H.F.R. apparatus could be redesigned to allow for lateral movement of the test specimen, thus permitting a range of tests on the same liner specimen.
- 2) The mounting of the outer oil bath could be redesigned in order to eliminate vibration, as seen on the oscilloscope trace.

3) To achieve closer similarity with engine tests, the drip feed tests could be conducted in an environment of exhaust gas from a running engine. This would allow the proposed bore polishing mechanism to be placed in context with polishing by combustion products.

4) The effect of materials on bore polishing could be investigated in several ways :

a) The use of different cast irons. e.g. Spheroidal graphite cast iron.

b) The use of different surface profiles. e.g. Vibro-rolled cylinder bores, deep honing pattern.

c) The use of different piston ring profiles and coatings.

5) There is plenty of scope for investigation into the role of lubricant and additives. e.g.

a) E.P. additives such as DBDS.

b) Antioxidants.

c) Dispersants and detergents.

Appendix

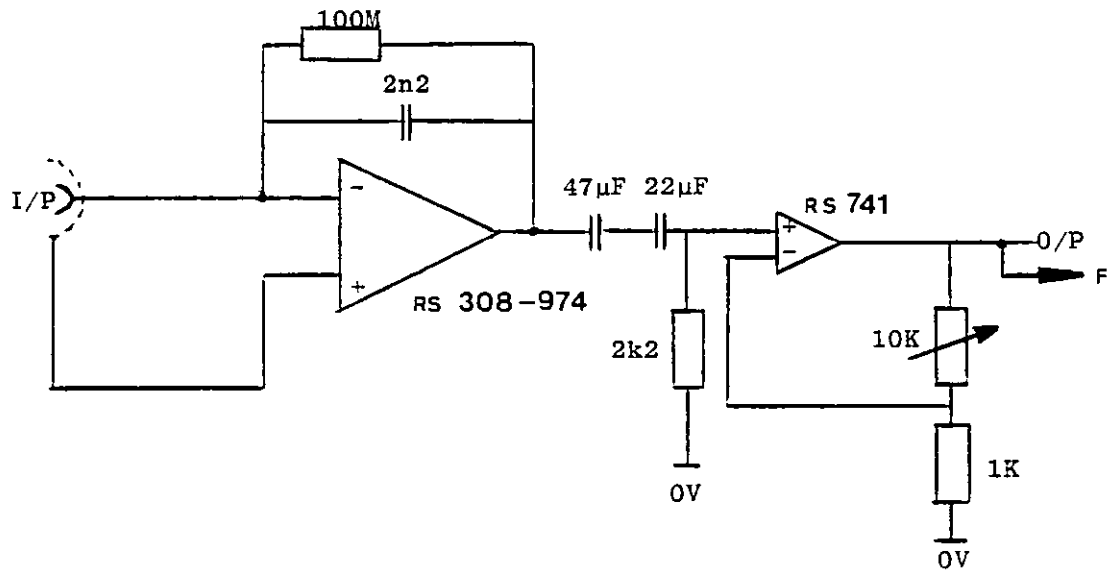


Fig A-1 FORCE AMPLIFIER

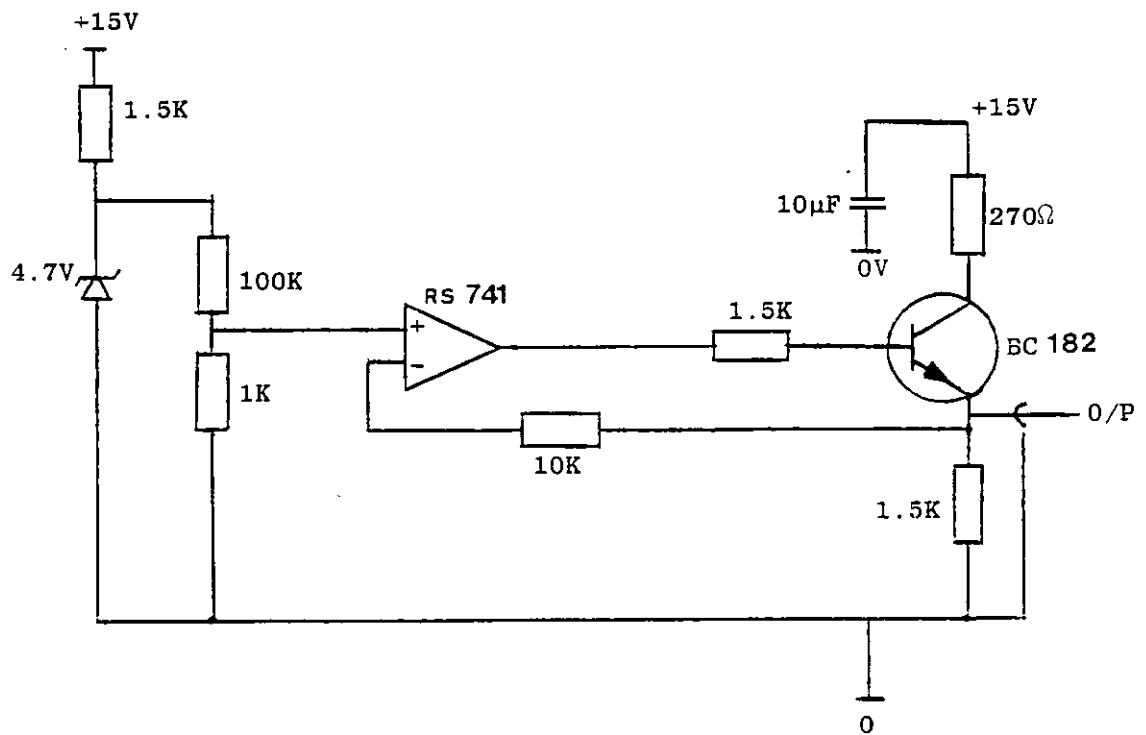


Fig A-2 16mV CONSTANT VOLTAGE SOURCE

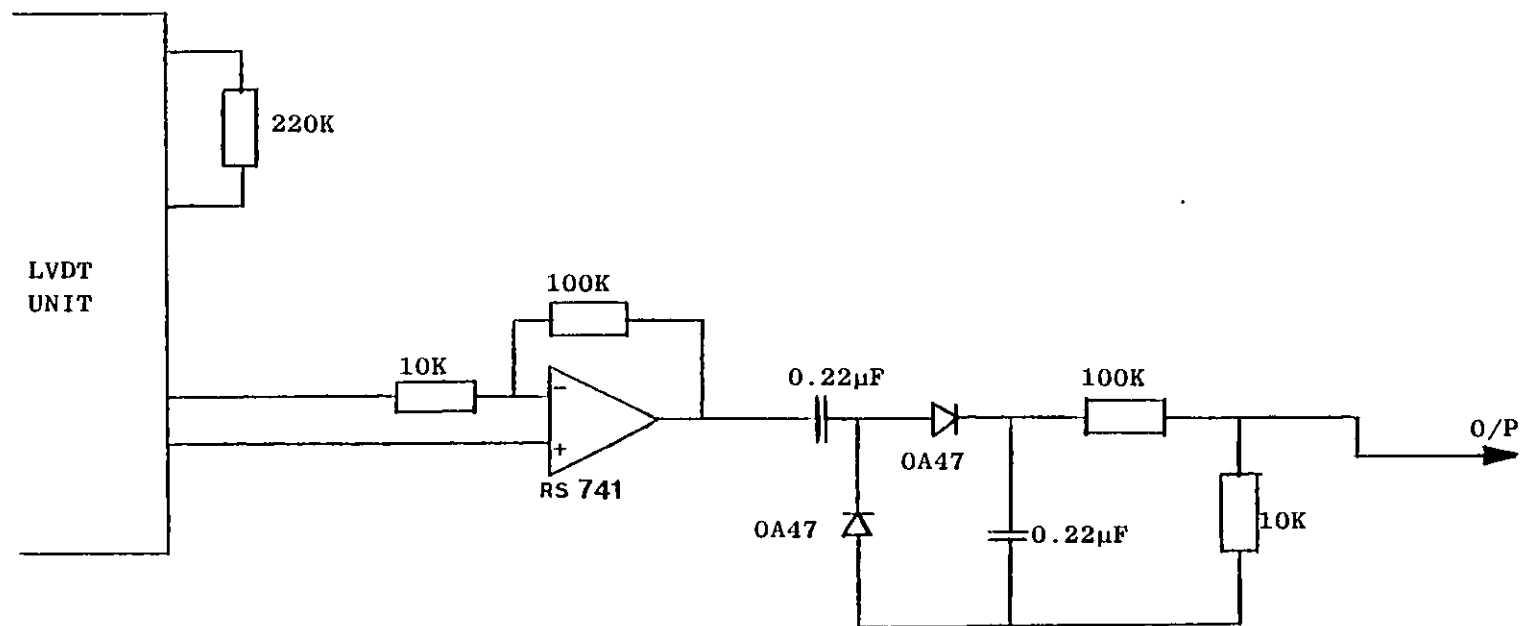


Fig A-3 DISPLACEMENT PEAK

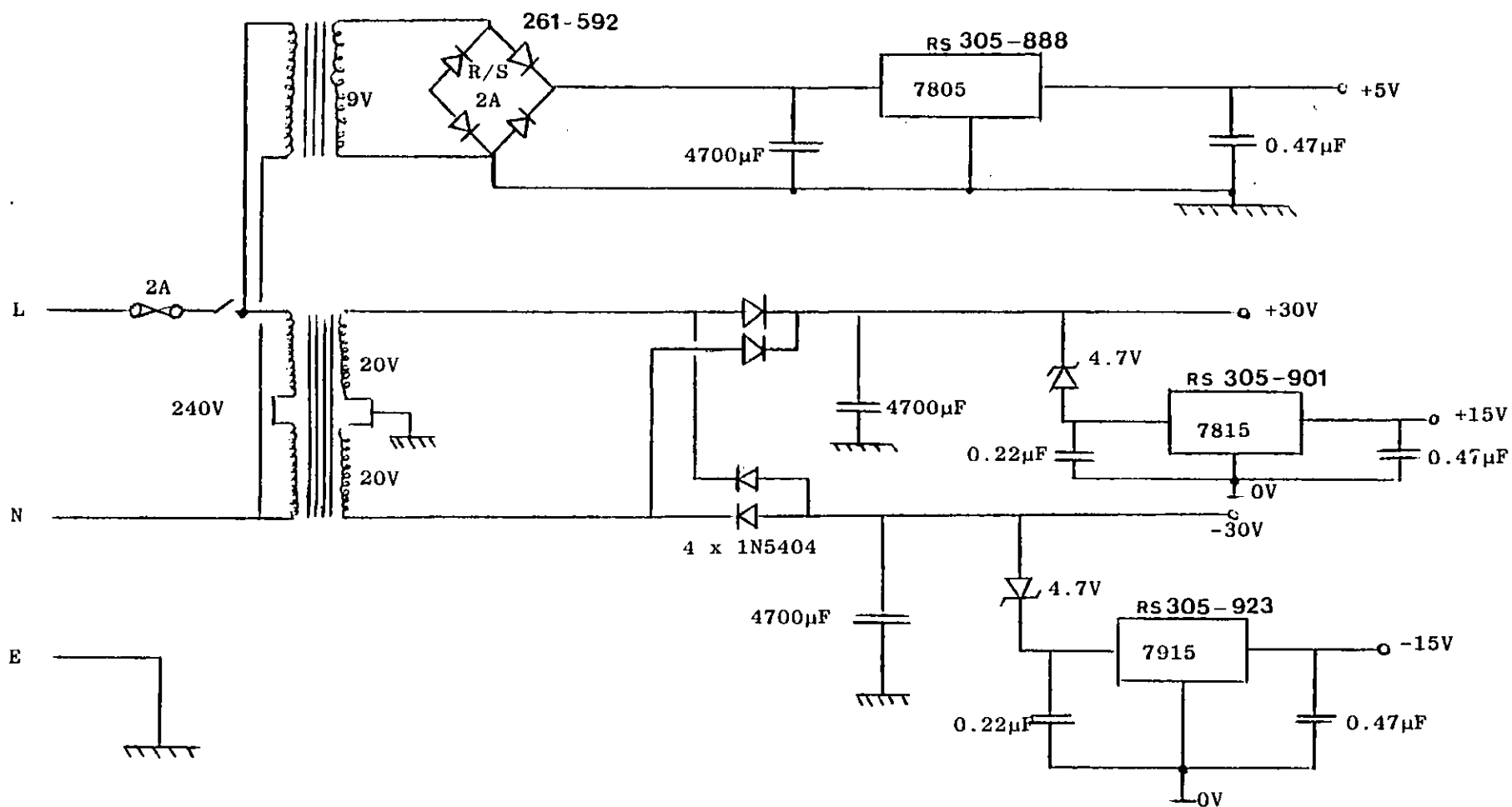


Fig A-4 POWER SUPPLY UNIT



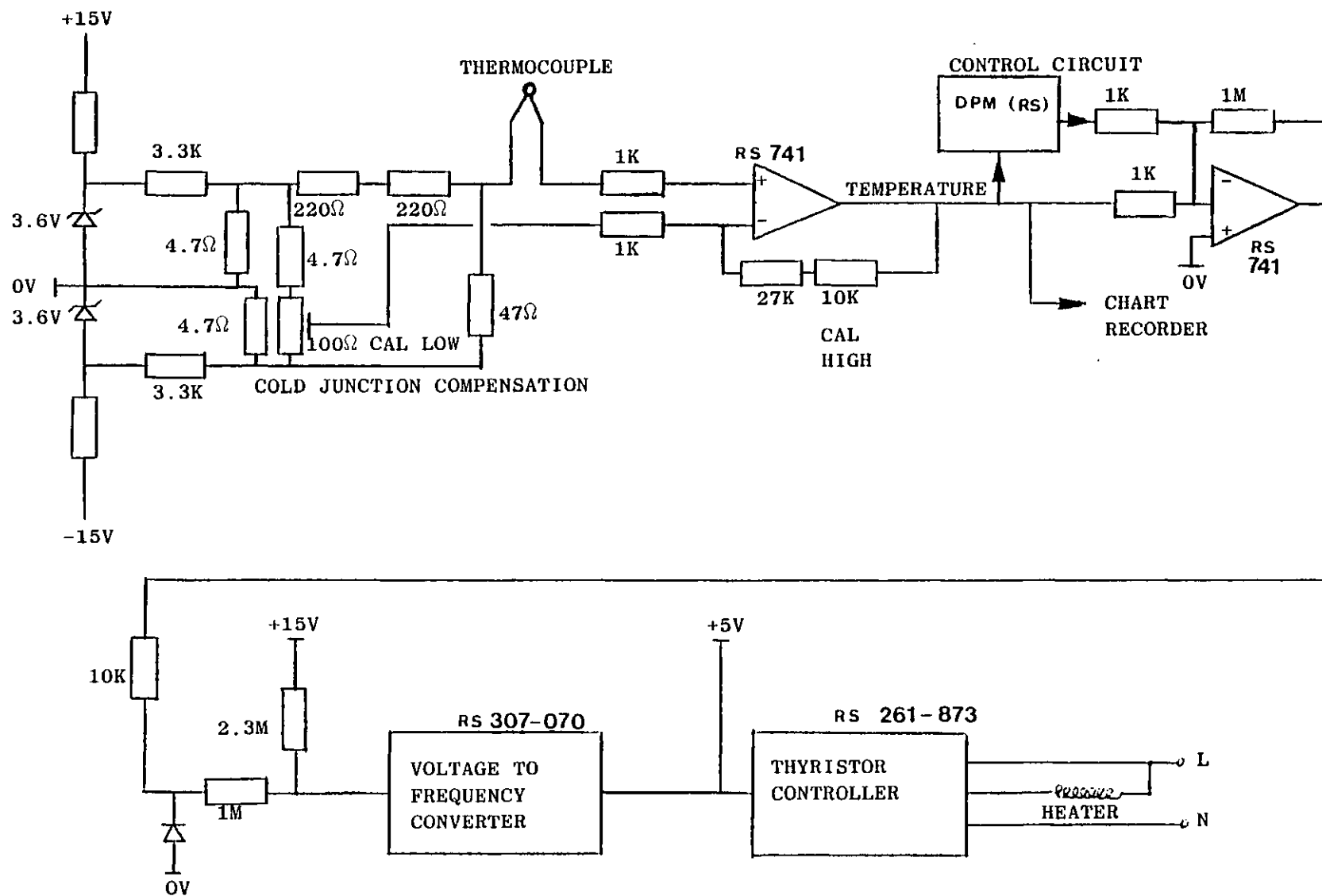


Fig A-5 TEMPERATURE CONTROLLER

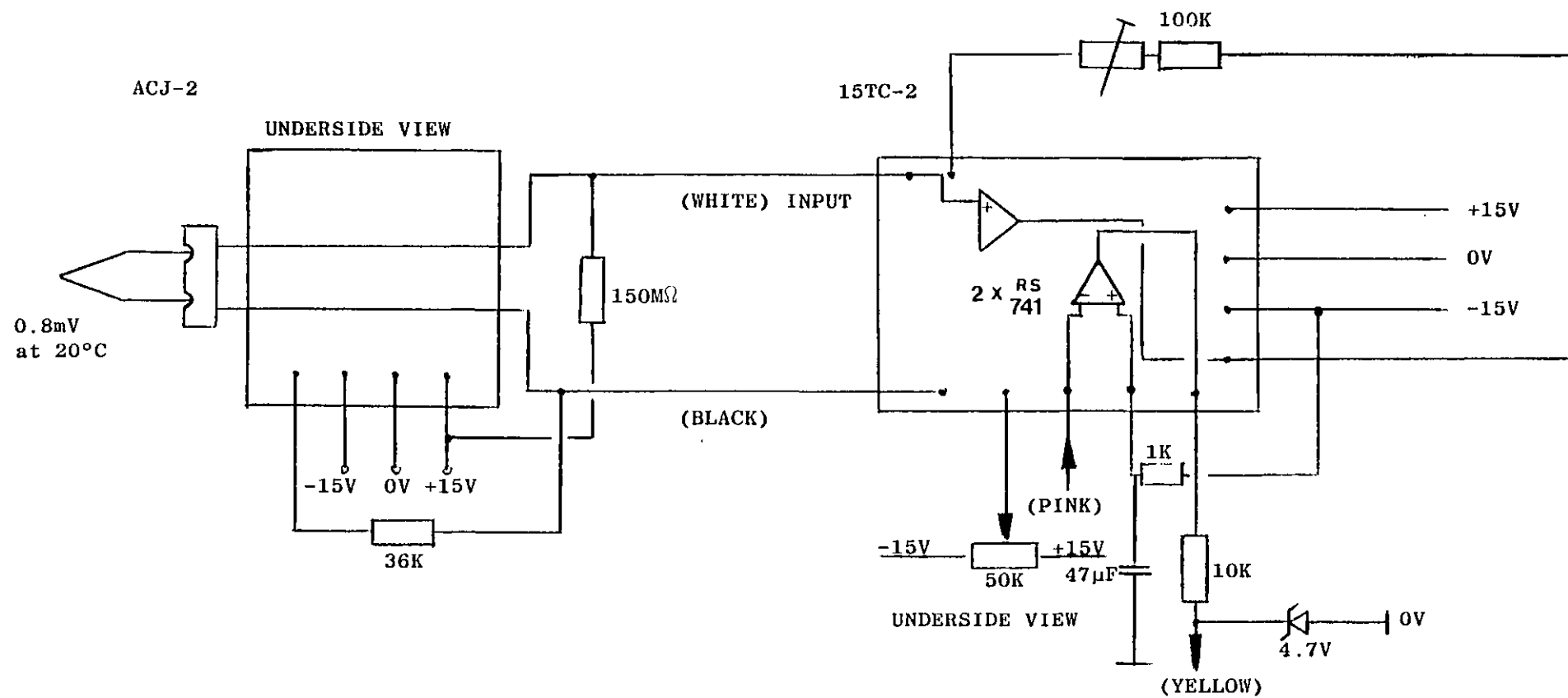
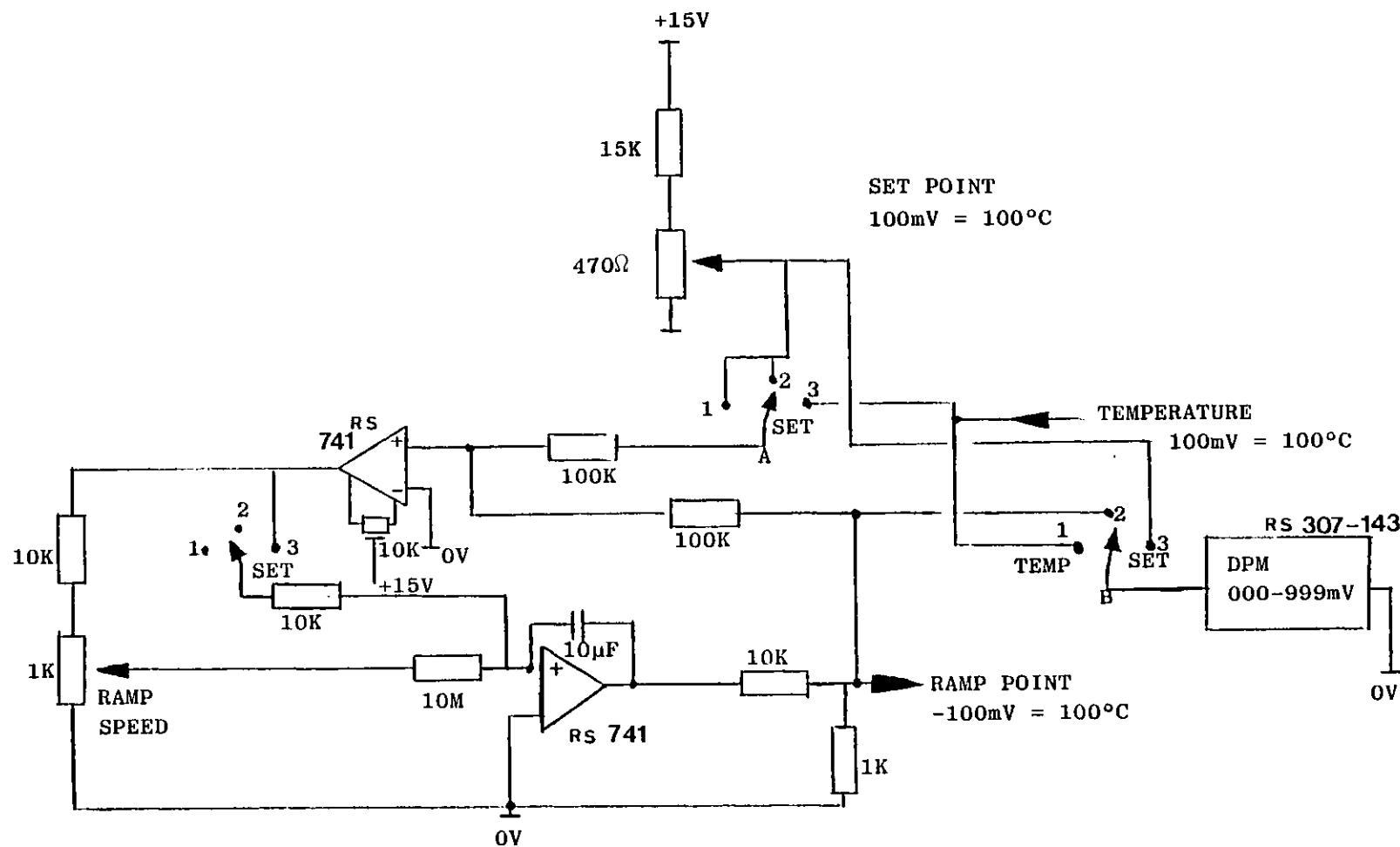


Fig A-6 THERMOCOUPLE AMPLIFIER



A-7 SET POINT CONTROL CIRCUIT

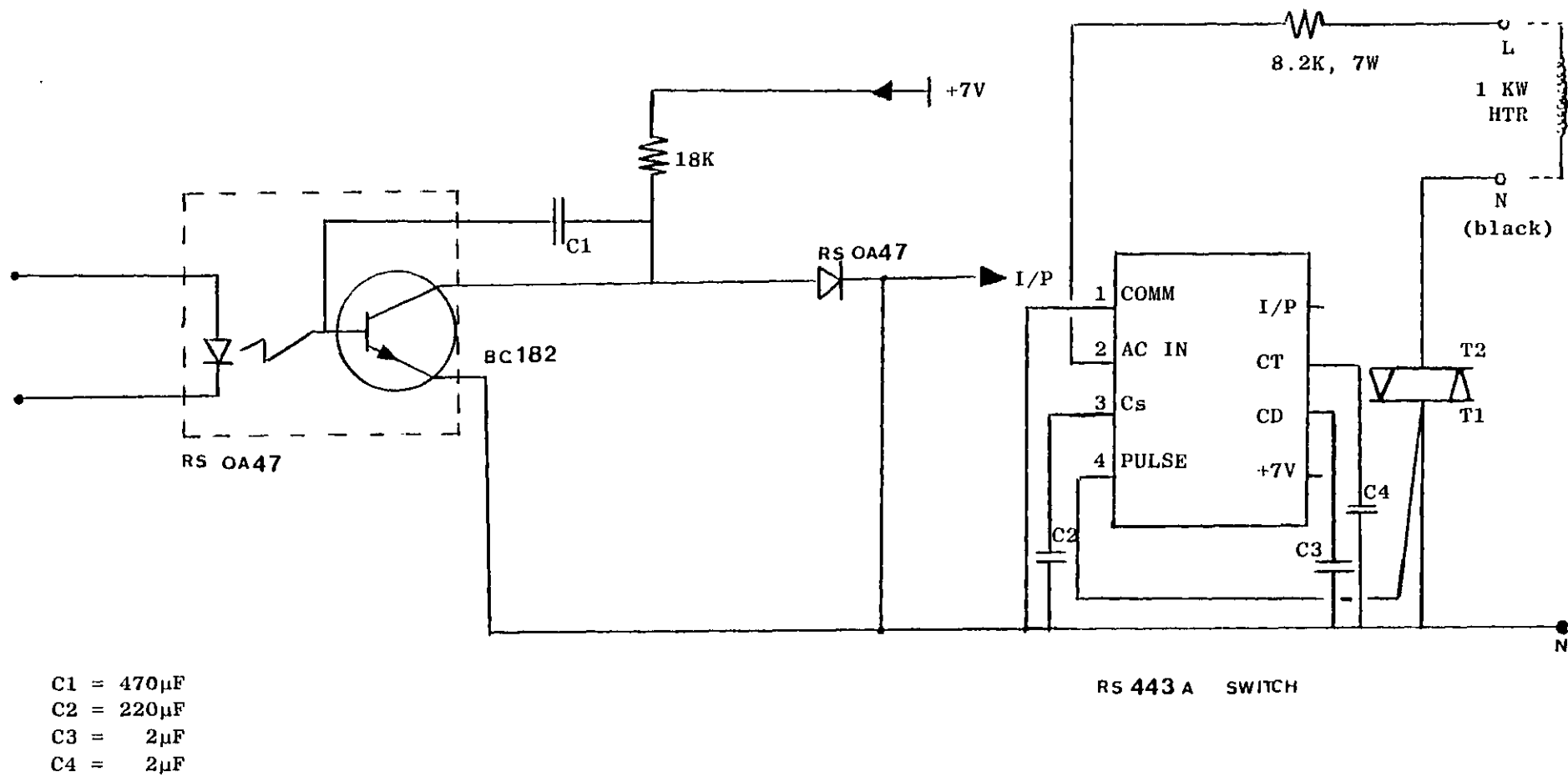
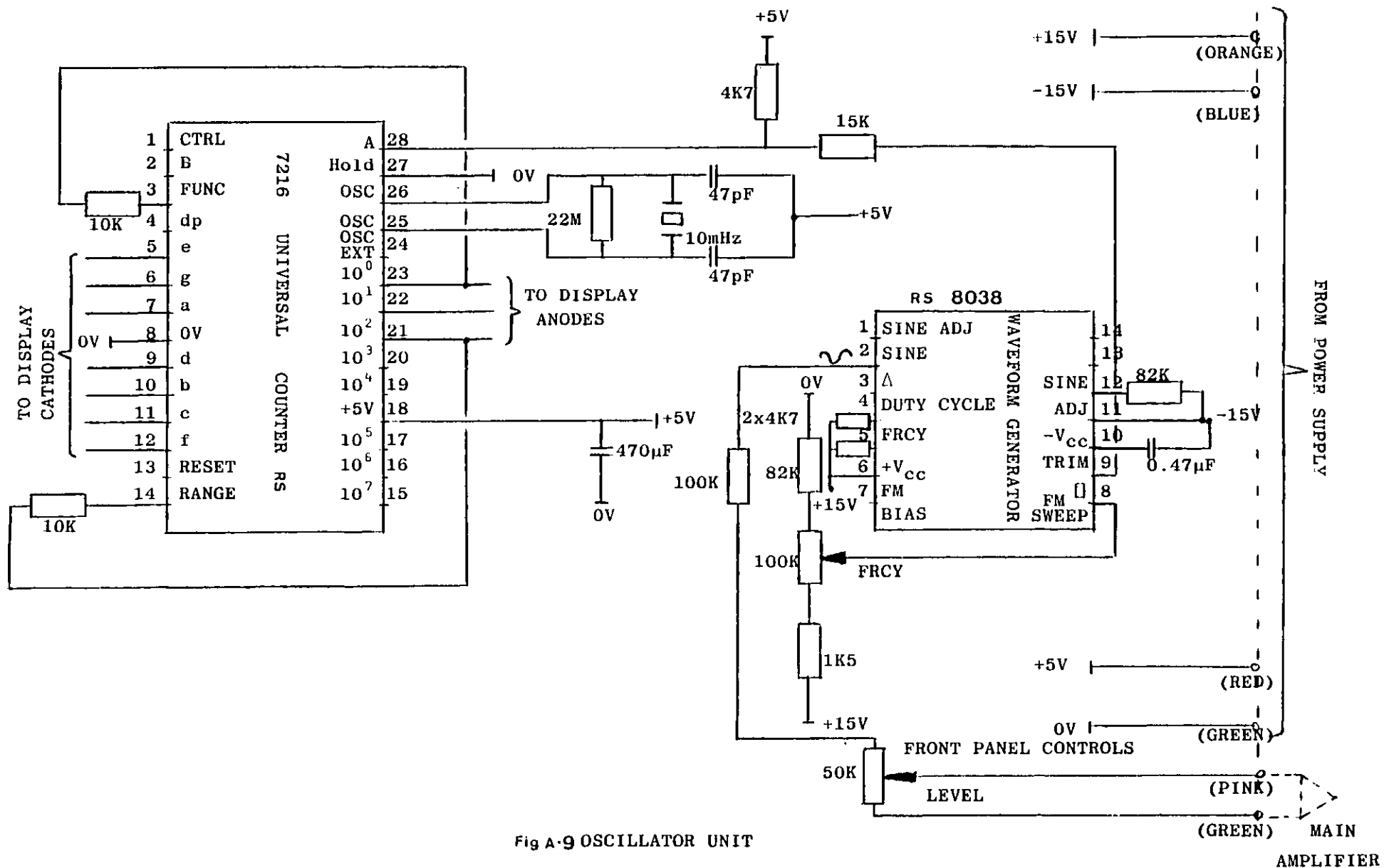


Fig A-8 HEATER CONTROL UNIT



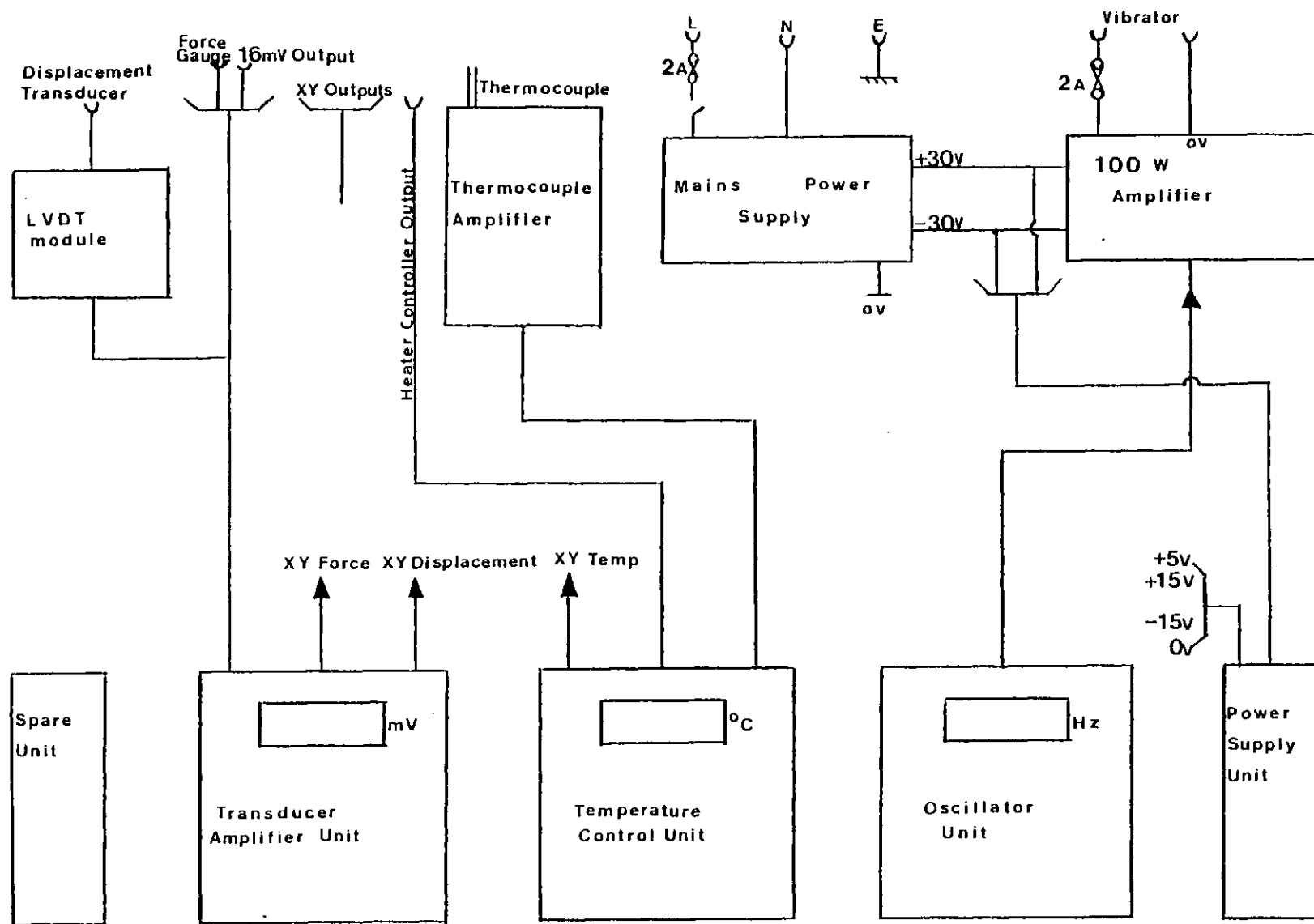


Fig A-10 Schematic of circuits

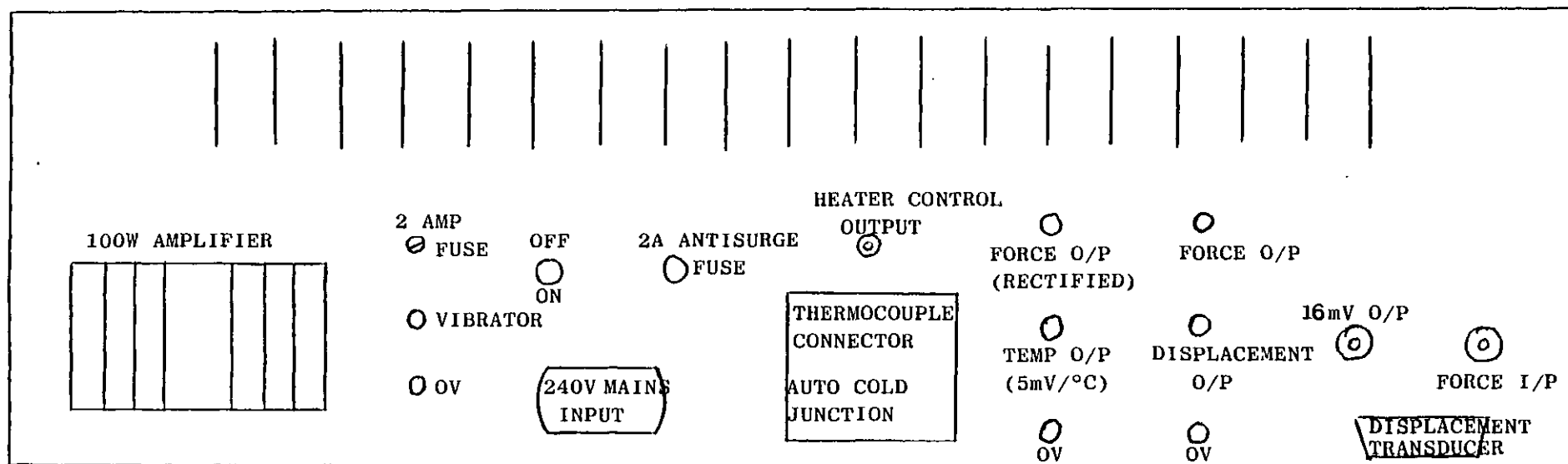


Fig A-11 BACK PANEL OF INSTRUMENT

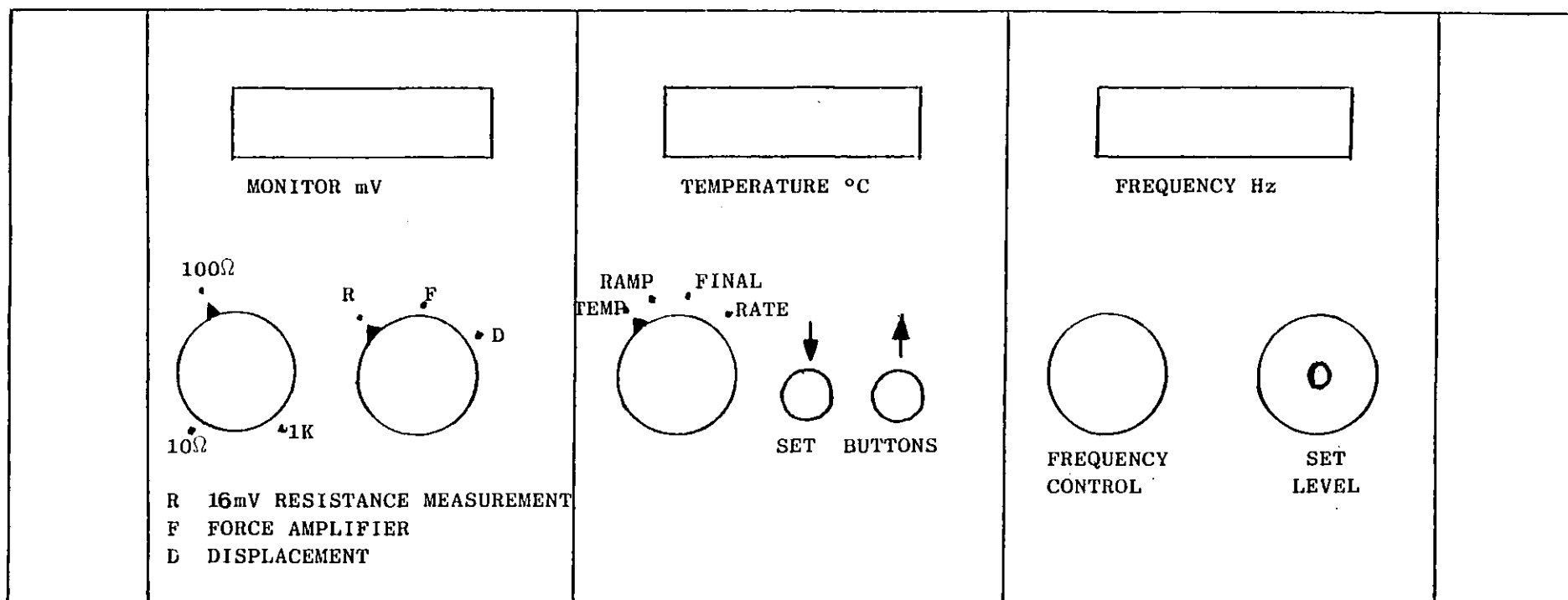


Fig A-12 CONTROL PANEL



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